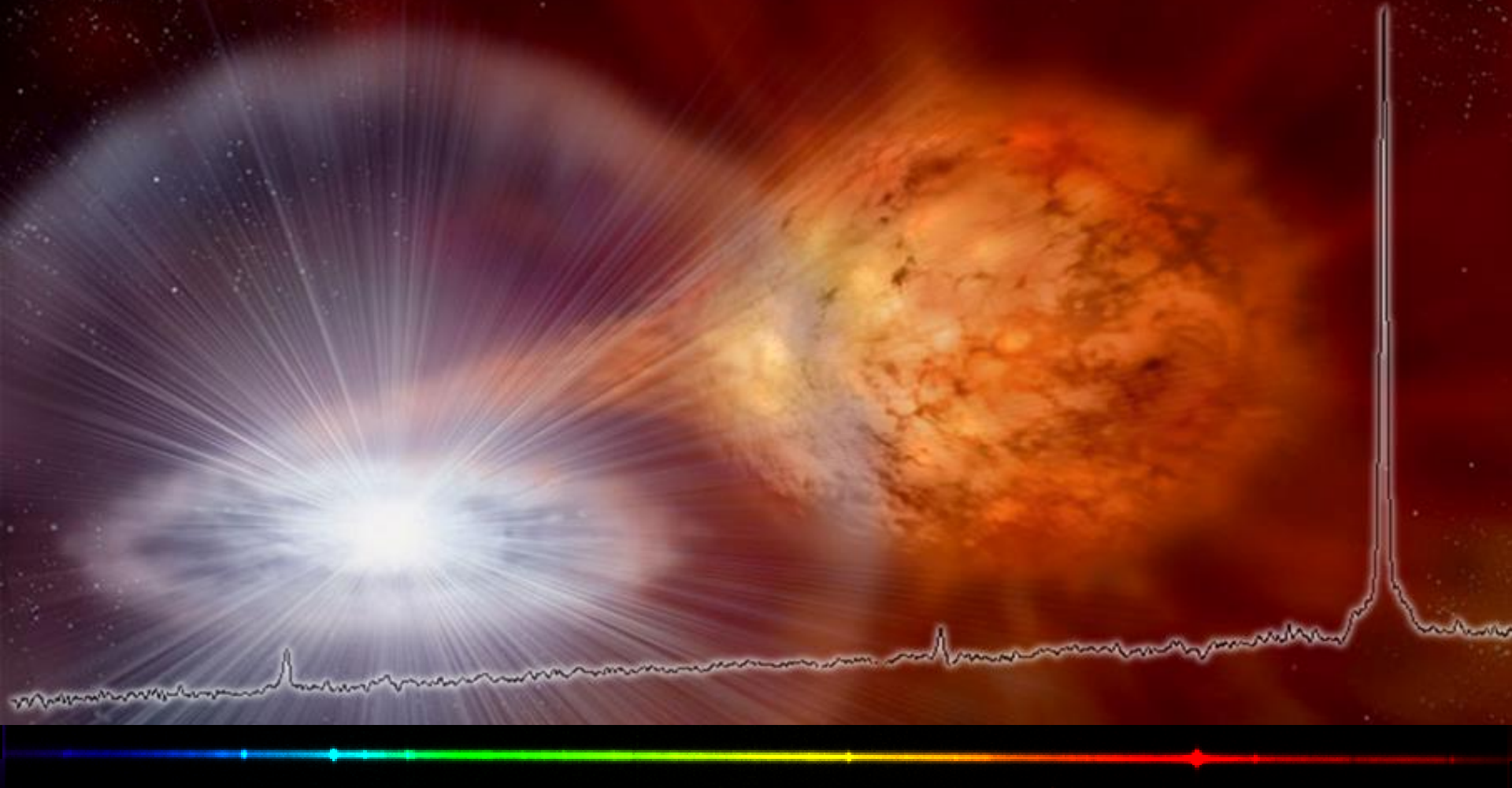


Etoiles Symbiotiques



Mons,
23-04-2017

François Teyssier
www.astronomie-amateur.fr

1 Spectroscopie et Classification spectrale

2 La découverte des Etoiles Symbiotiques

3 Modèle d'une Etoile Symbiotique

4 Formation du spectre

5 Les Symbiotiques à l'état calme

6 Le Zoo des Symbiotiques

7 Les Symbiotiques en Outburst

8 Contribution des amateurs

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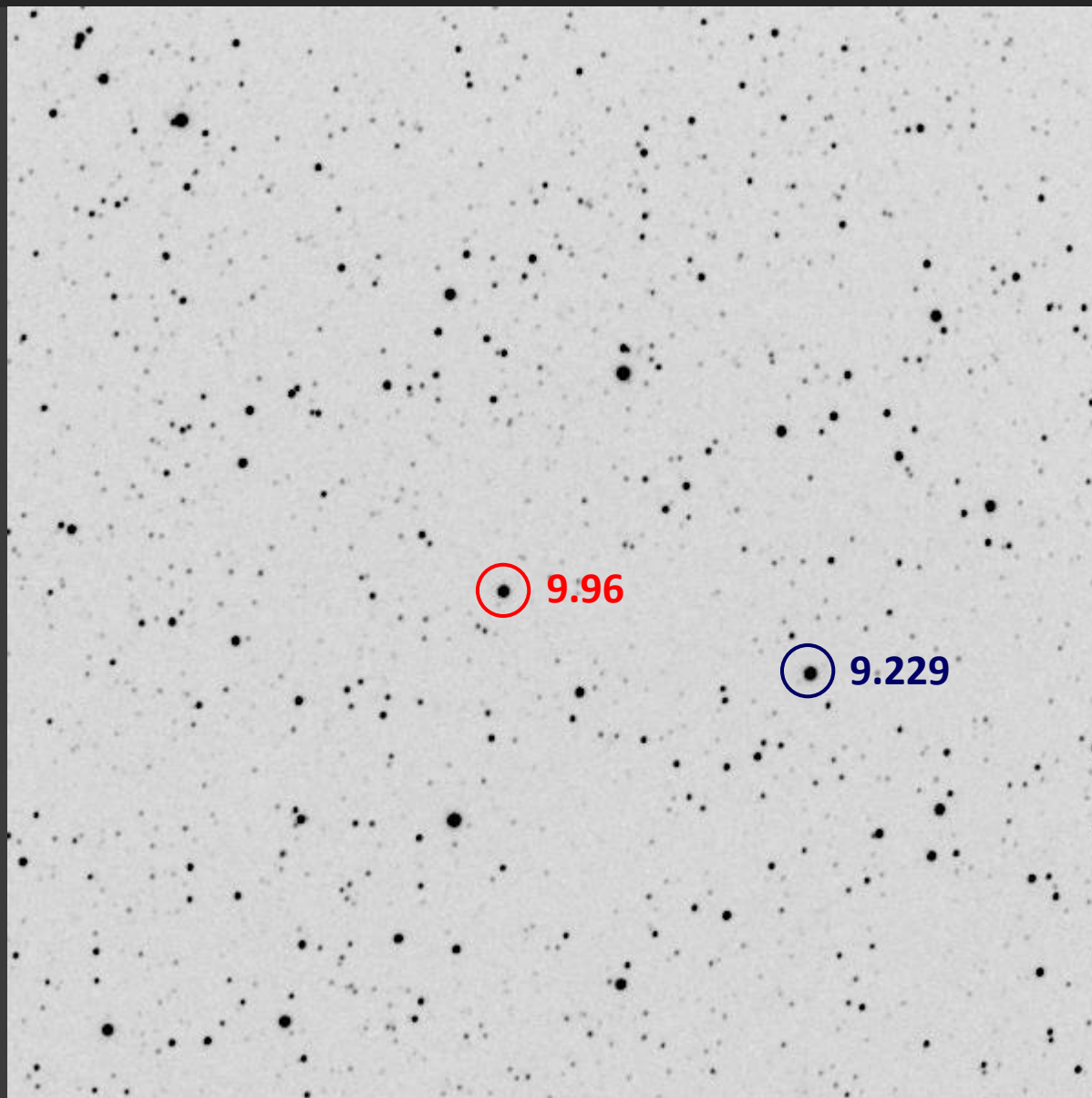
Z And

V filter

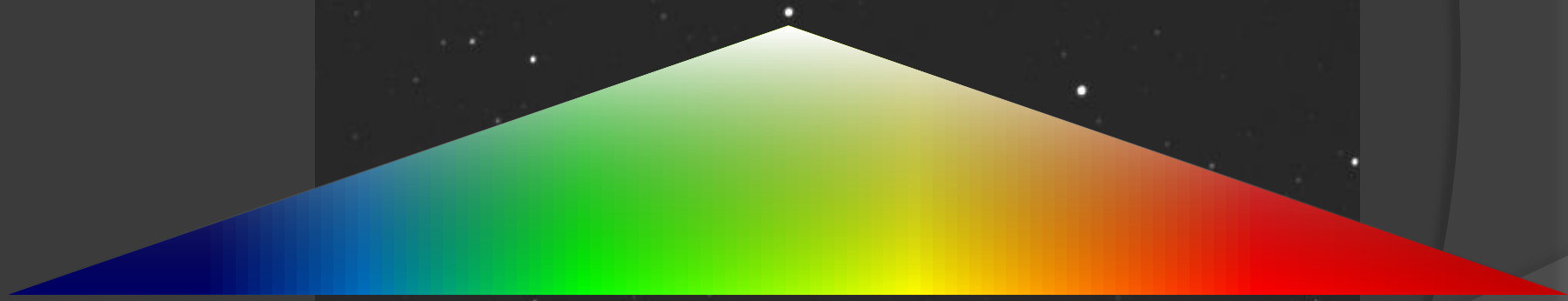
13-08-2016

22:06 UT

OHP (FR)



Spectroscopie

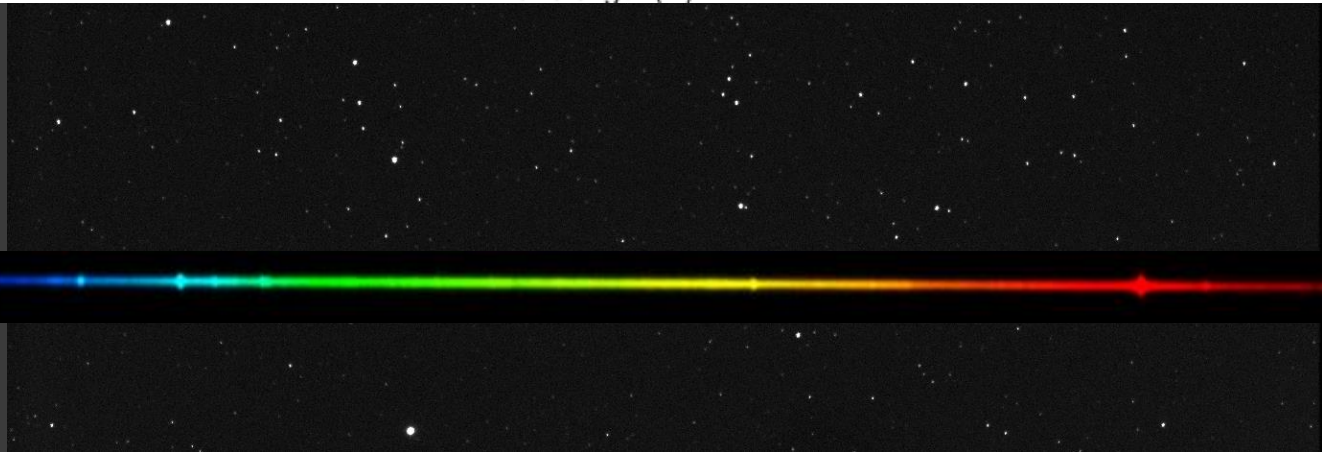
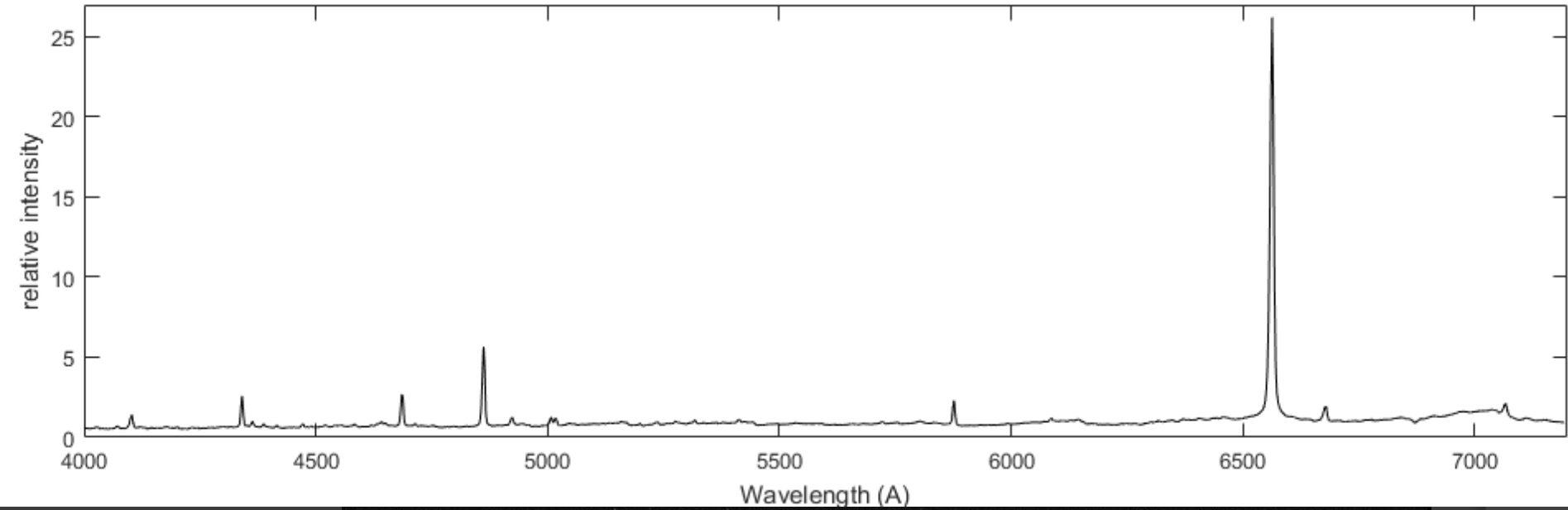


4000 Å

7500 Å

Spectroscopie

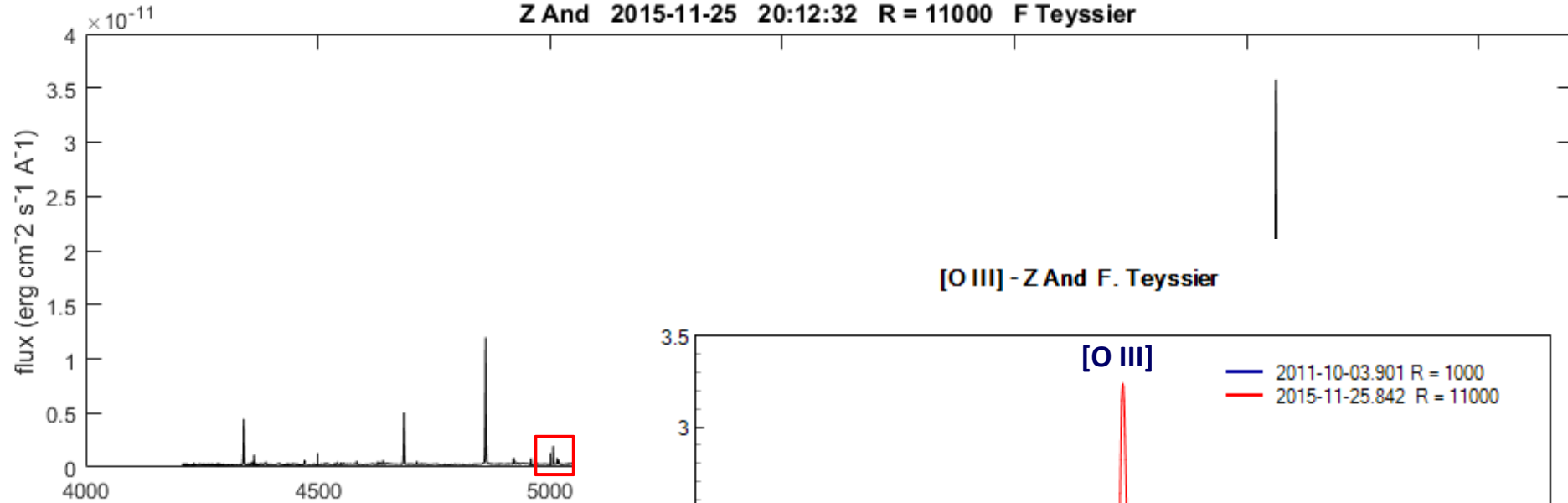
Z And 2012-09-08 21:28:03 R = 1000 François Teyssier



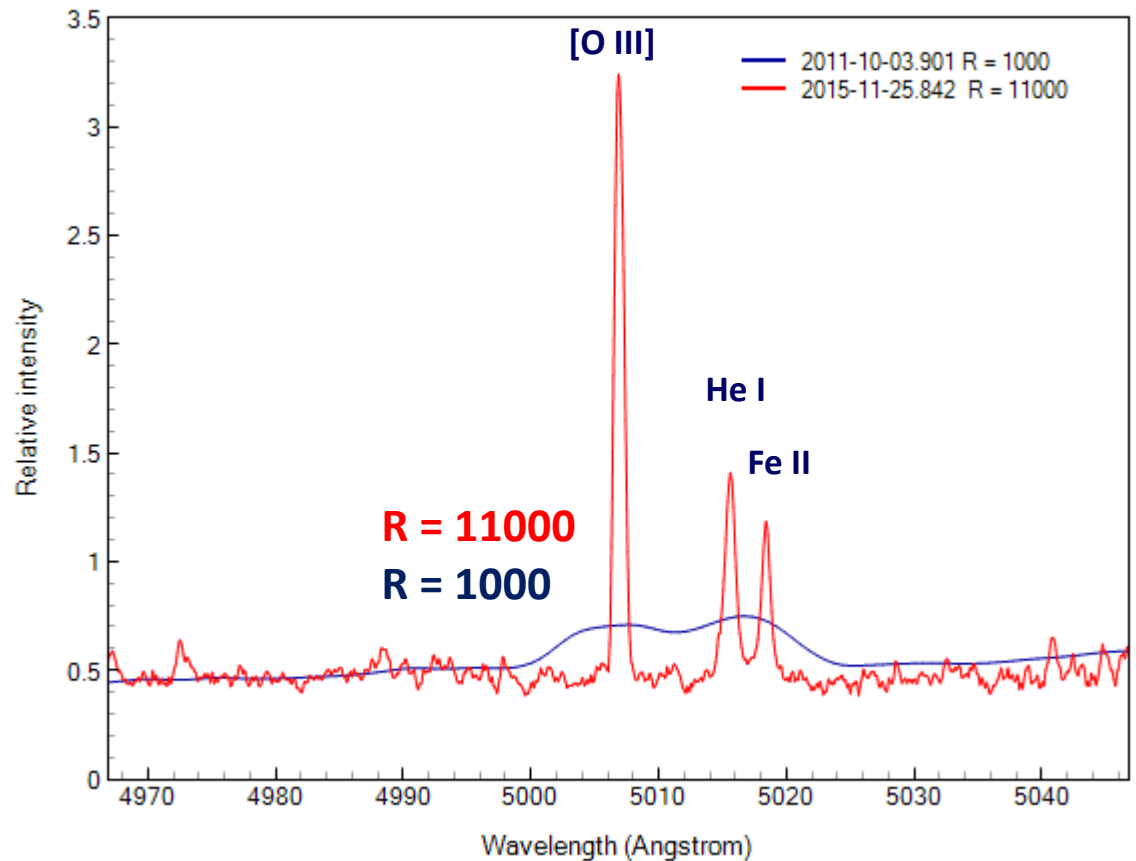
4000 Å

7500 Å

Z And 2015-11-25 20:12:32 R = 11000 F Teyssier



[O III] - Z And F. Teyssier

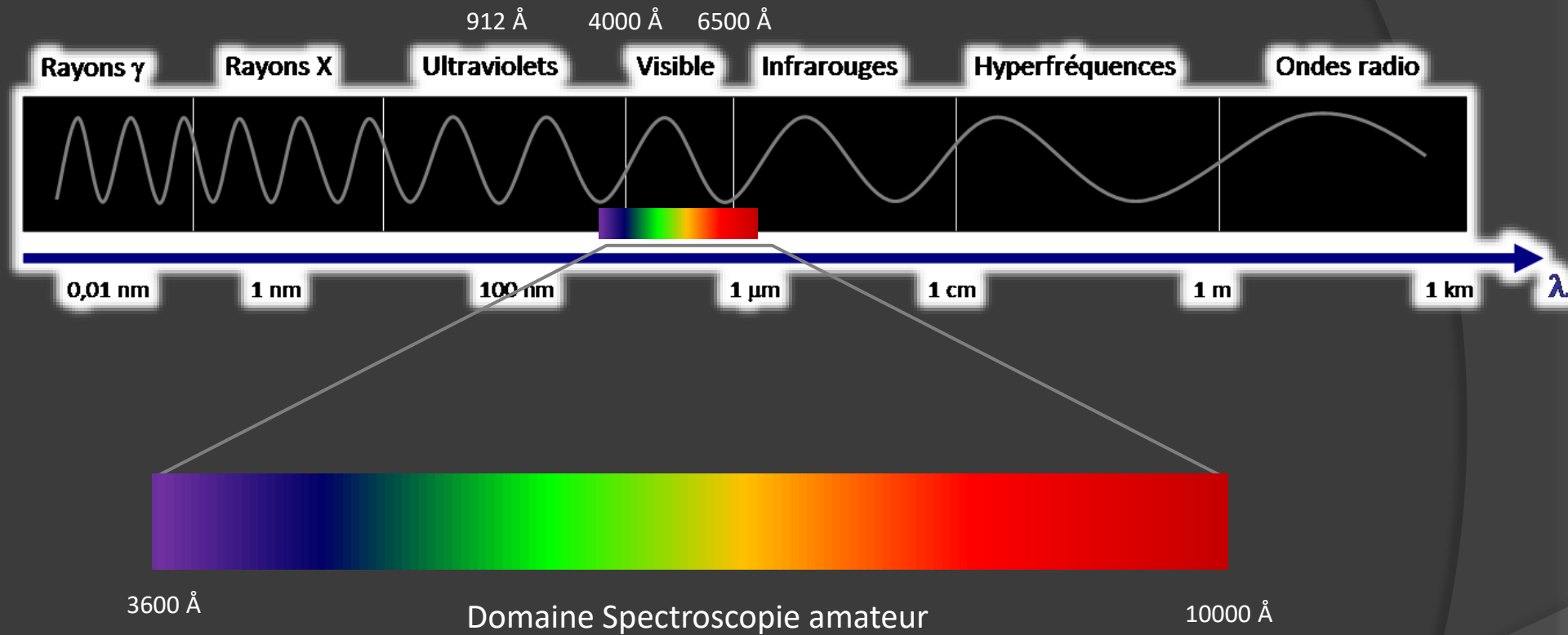


Résolution

$$R = \lambda / \Delta\lambda$$

Basse	500-1000
Moyenne	2000-5000
Haute	10000-15000

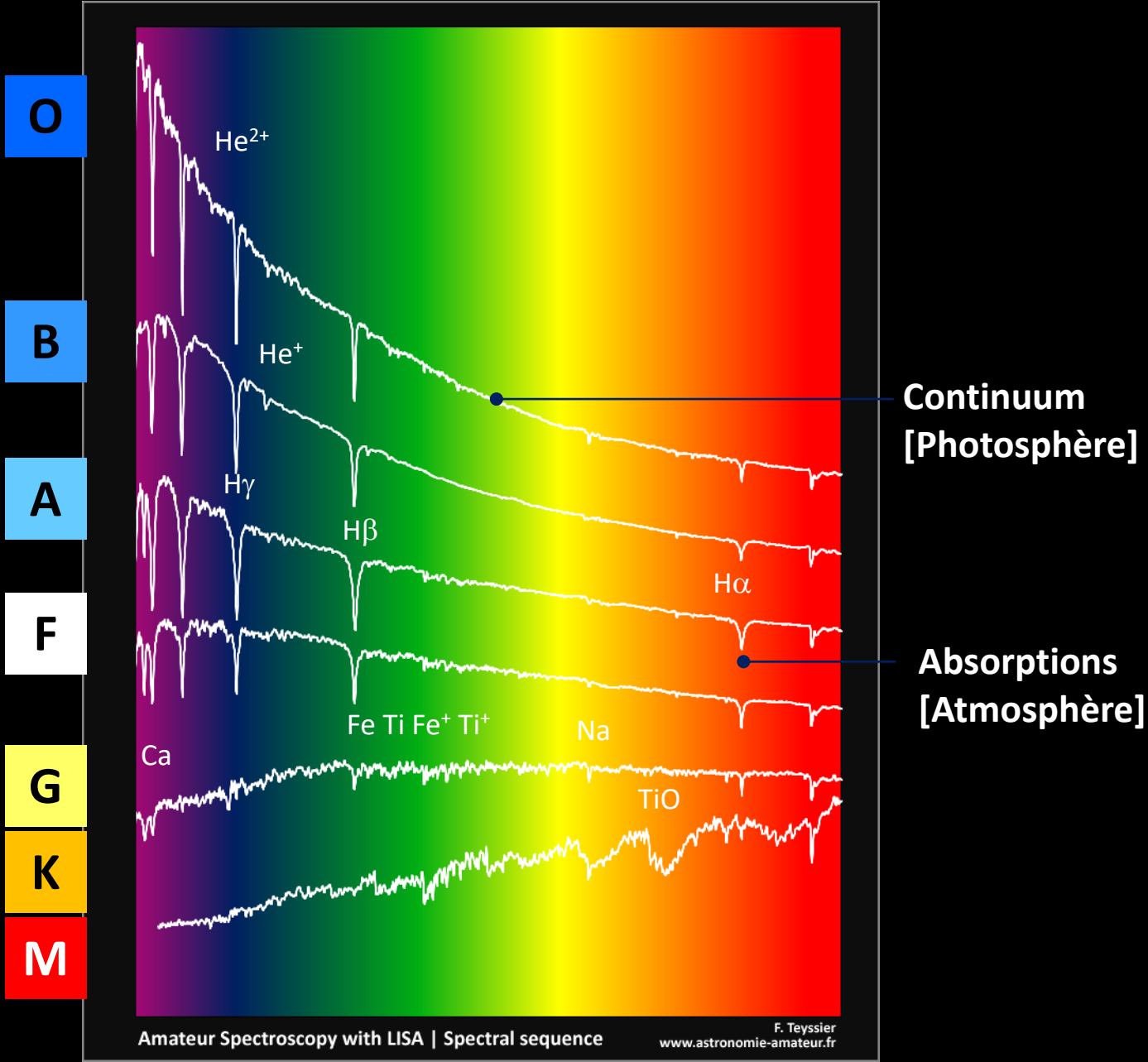
Spectroscopie



Unité usuelle : Angström [Å]

1 nm = 10 Å

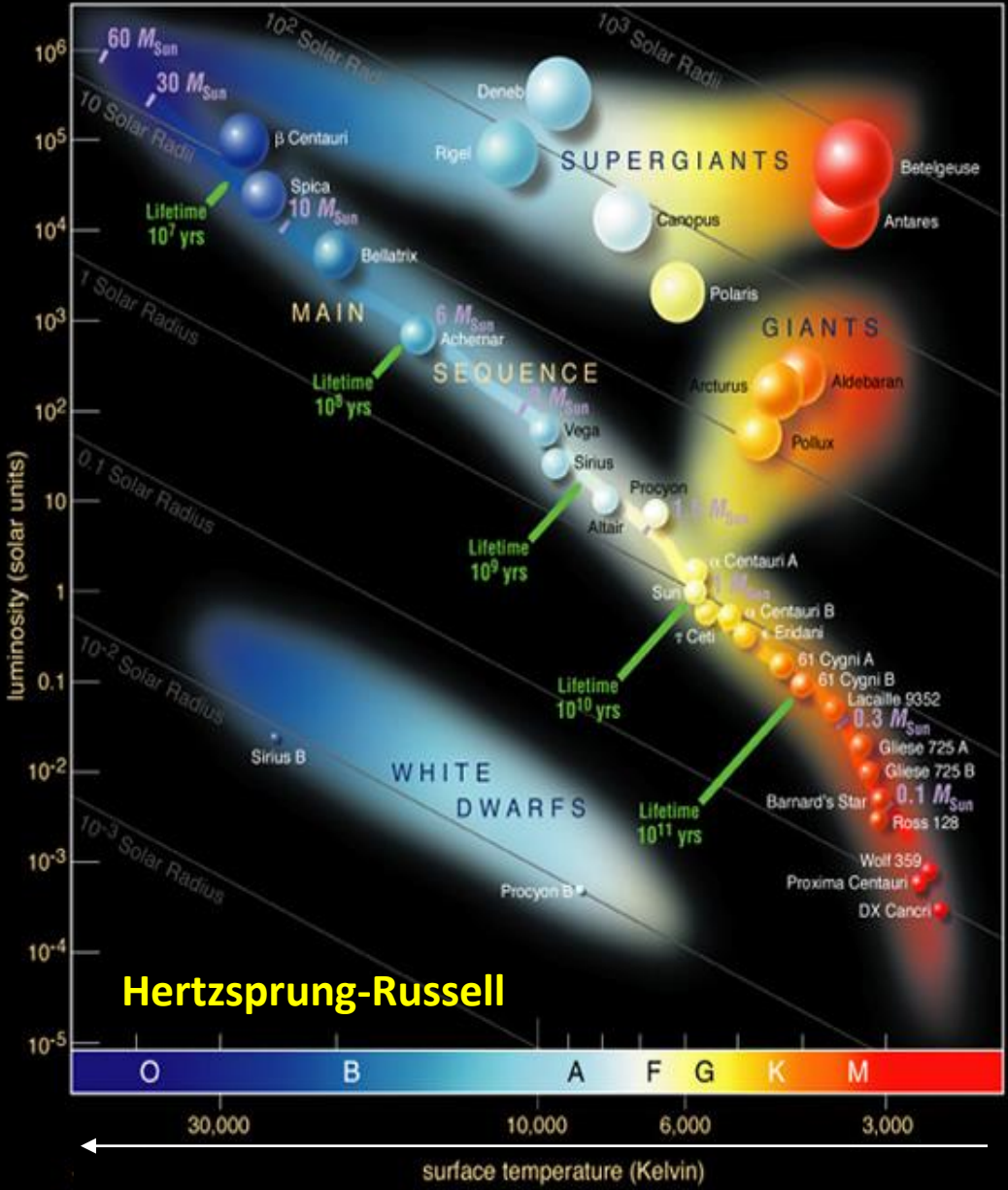
Classification spectrale



Classification spectrale

Catalogue HD (Henri Draper) XIX-XX^e
 Williamina Fleming
 Annie Cannon

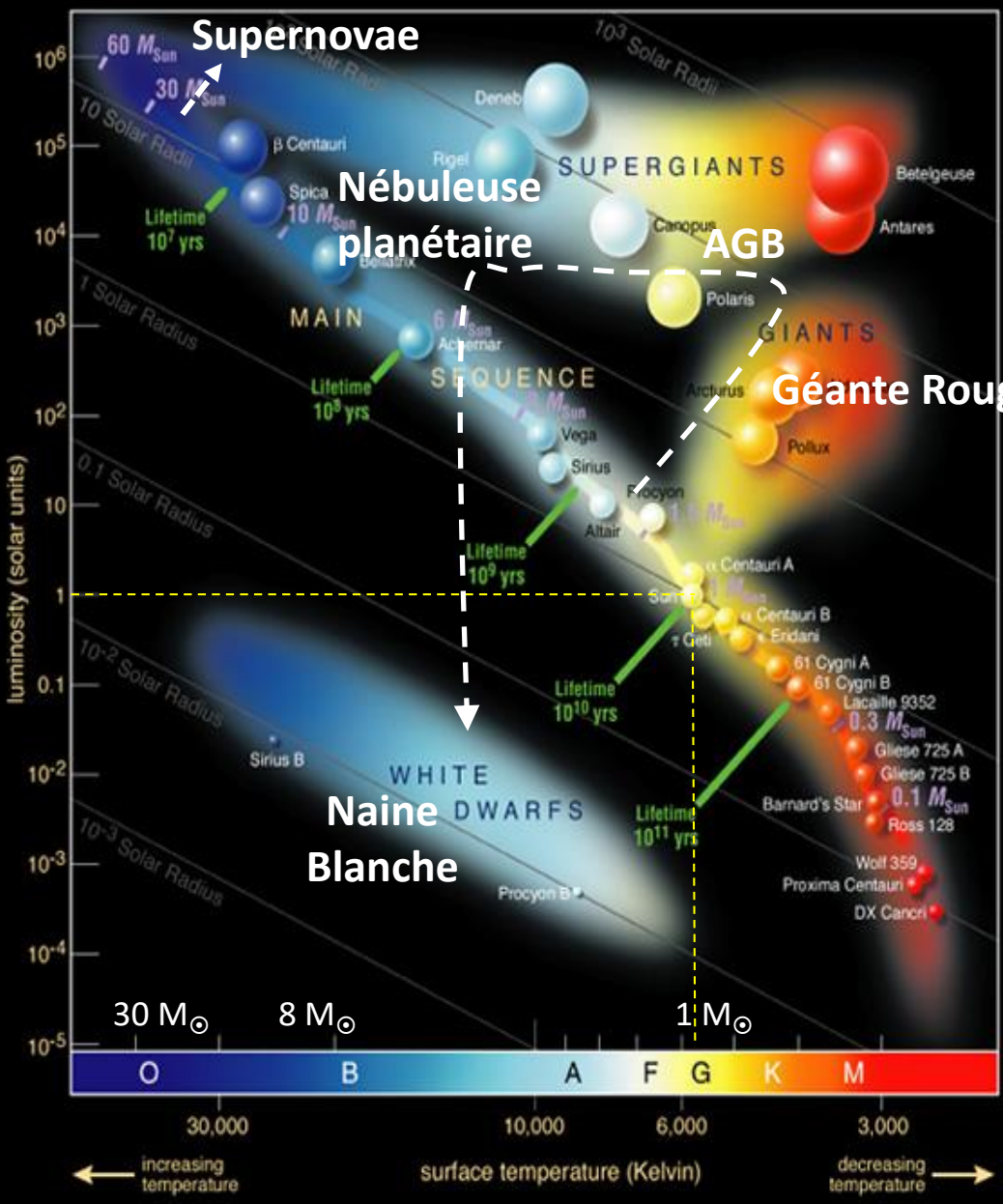
Séquence principale



O	30000 K	16 M _⊙	6.6 R _⊙	30000 L _⊙
B	10000 K	2.1 M _⊙	1.8 R _⊙	25 L _⊙
A	7500 K	1.4 M _⊙	1.4 R _⊙	5 L _⊙
F	6000 K	1.04 M _⊙	1.15 R _⊙	1.5 L _⊙
G	5200 K	0.8 M _⊙	0.96 R _⊙	0.6 L _⊙
K	3700 K	0.45 M _⊙	0.7 R _⊙	0.08 L _⊙
M				

Classification spectrale

Evolution stellaire



Supernovae

Nébuleuse
planétaire

AGB

Géante Rouge

White
Dwarfs
Naine
Blanche

$30 M_{\odot}$

$8 M_{\odot}$

$1 M_{\odot}$

O

B

A

F

G

K

M

30,000

10,000

6,000

3,000

← increasing temperature

surface temperature (Kelvin)

→ decreasing temperature

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Classification spectrale : étoiles inclassables

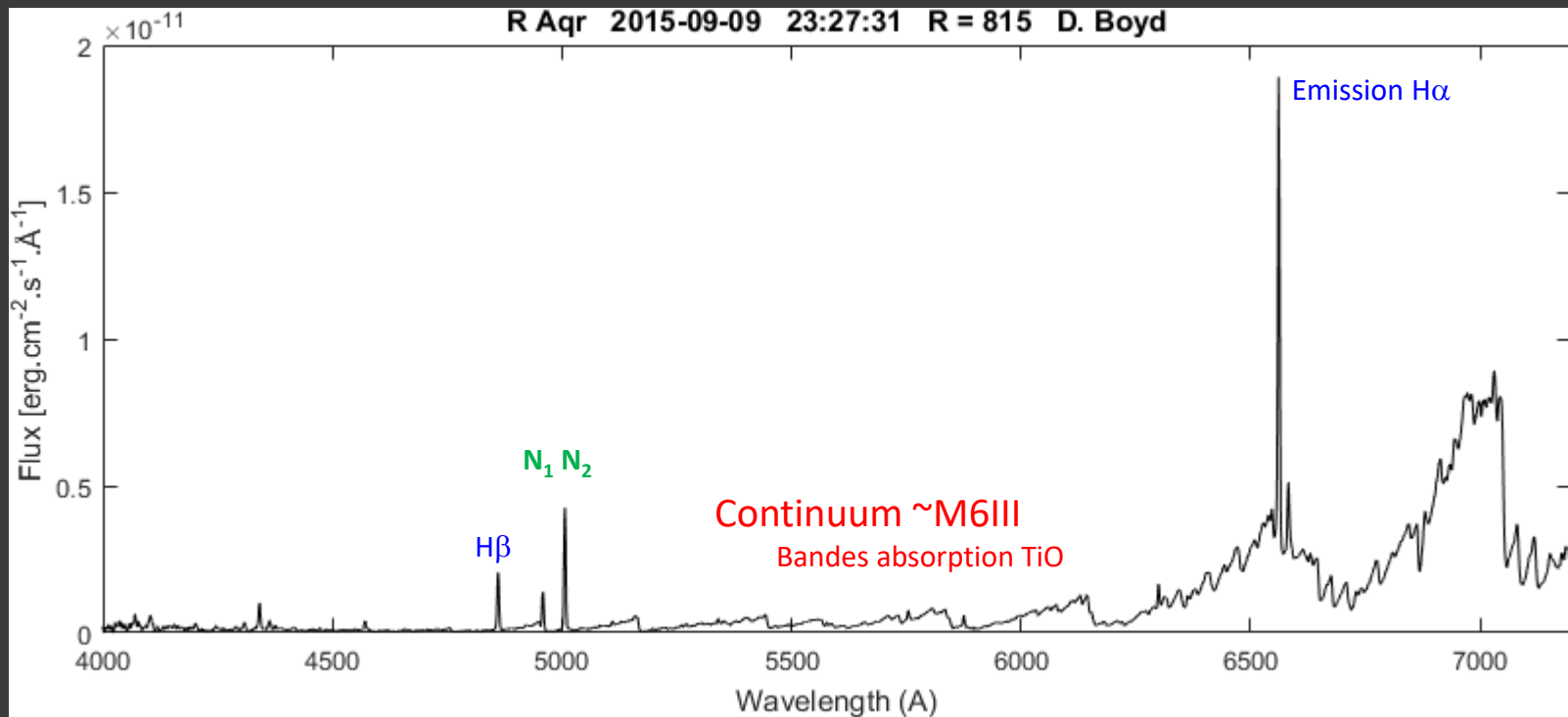
Merrill, 1919

R Aqr, l'ornithorynque :
« un spectre très particulier »

A VARIABLE STAR WITH A PECULIAR SPECTRUM

The long-period variable star R *Aquarii* 233815 has been found recently to possess a very peculiar spectrum. The data concerning

On the first three plates the chief nebular lines N₁ and N₂, and λ 4363 are very conspicuous. On the later plates they are relatively



N₁ N₂ : raies « interdites » O²⁺ [O III] 5007, 4959 Å

Classification spectrale : étoiles à spectre composite

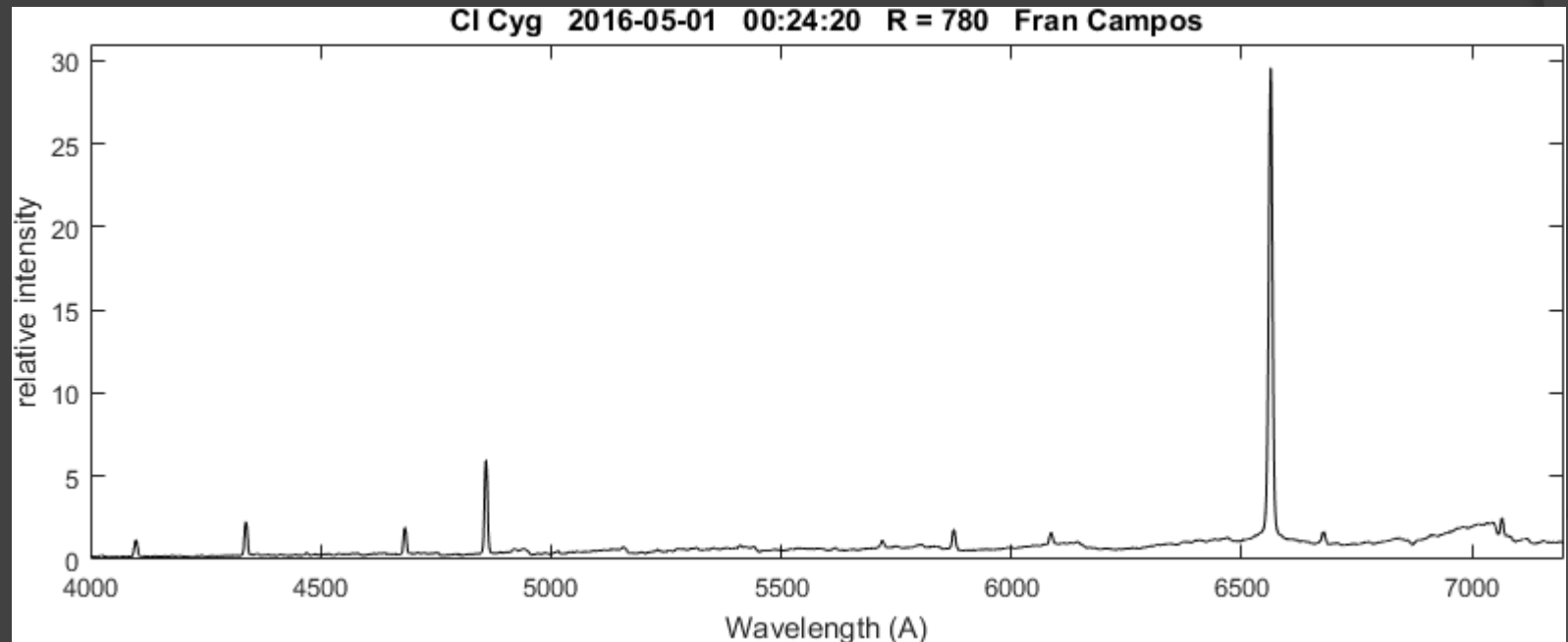
Merrill, 1932

A BRIGHT LINE OF IONIZED HELIUM, $\lambda 4686$, IN THREE
STELLAR SPECTRA WITH TITANIUM BANDS

In the spectra of these stars bright hydrogen lines and a narrow bright line of wave-length 4686A are superposed on a continuous background showing dark titanium bands whose intensities are about equal to those regularly found in class M4. The

1. Anon	1 ^h 31 ^m 8	+53° 52'
2. RW	<i>Hydrae</i>	13 30.2	-25 1
3. Anon	19 47.3	+35 29

AX Per
RW Hya
CI Cyg



jects for traces of titanium bands. It is of course difficult to understand why a high-excitation line of ionized helium should appear along with the spectrum of a molecule that is dissociated at a relatively low temperature.

Etoiles symbiotiques

Z And
Prototype dans GCVS

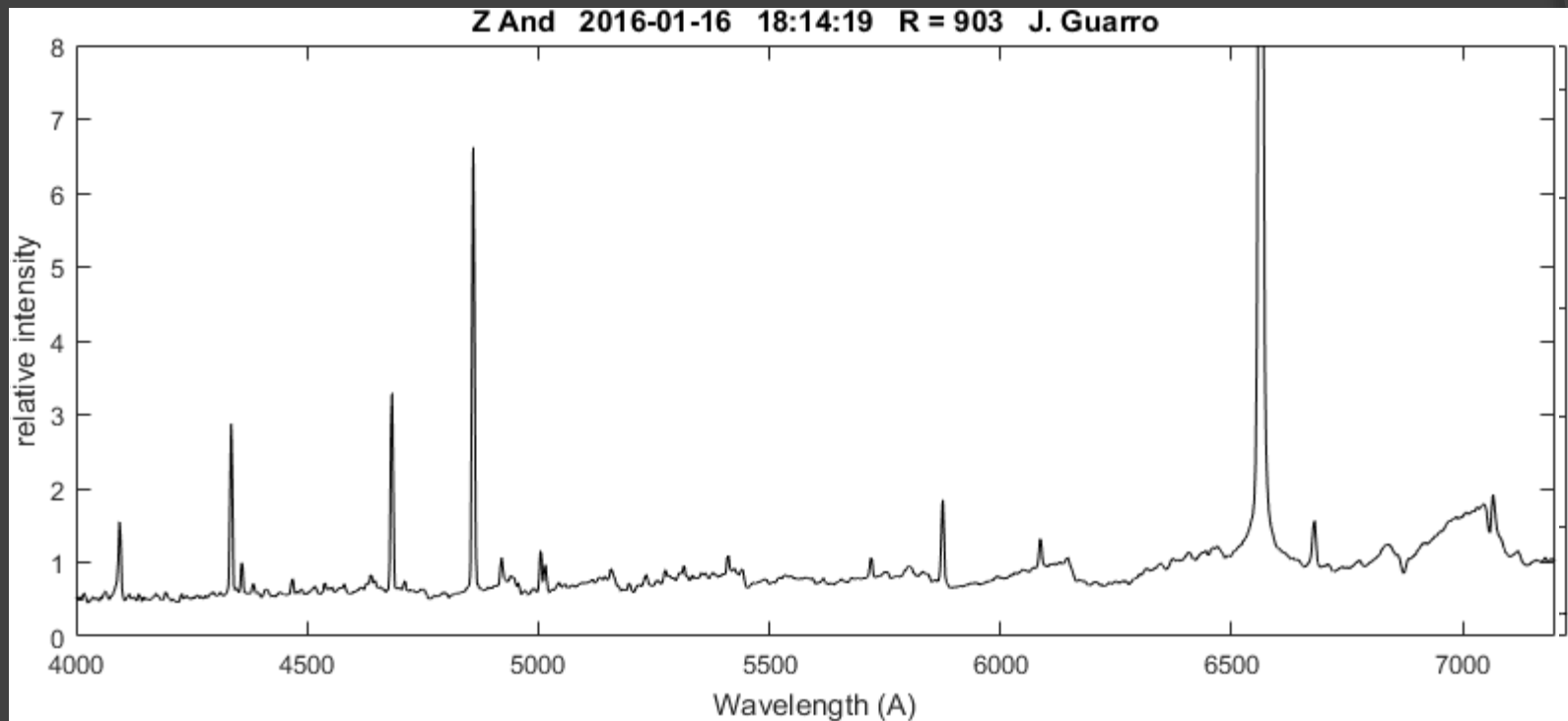
Phénomène symbiotique
Etoiles symbiotiques

Spectre absorption faible température
Raies fortement excitées en émission

Merrill, 1958

51 — SYMBIOSIS IN ASTRONOMY: INTRODUCTORY
REPORT

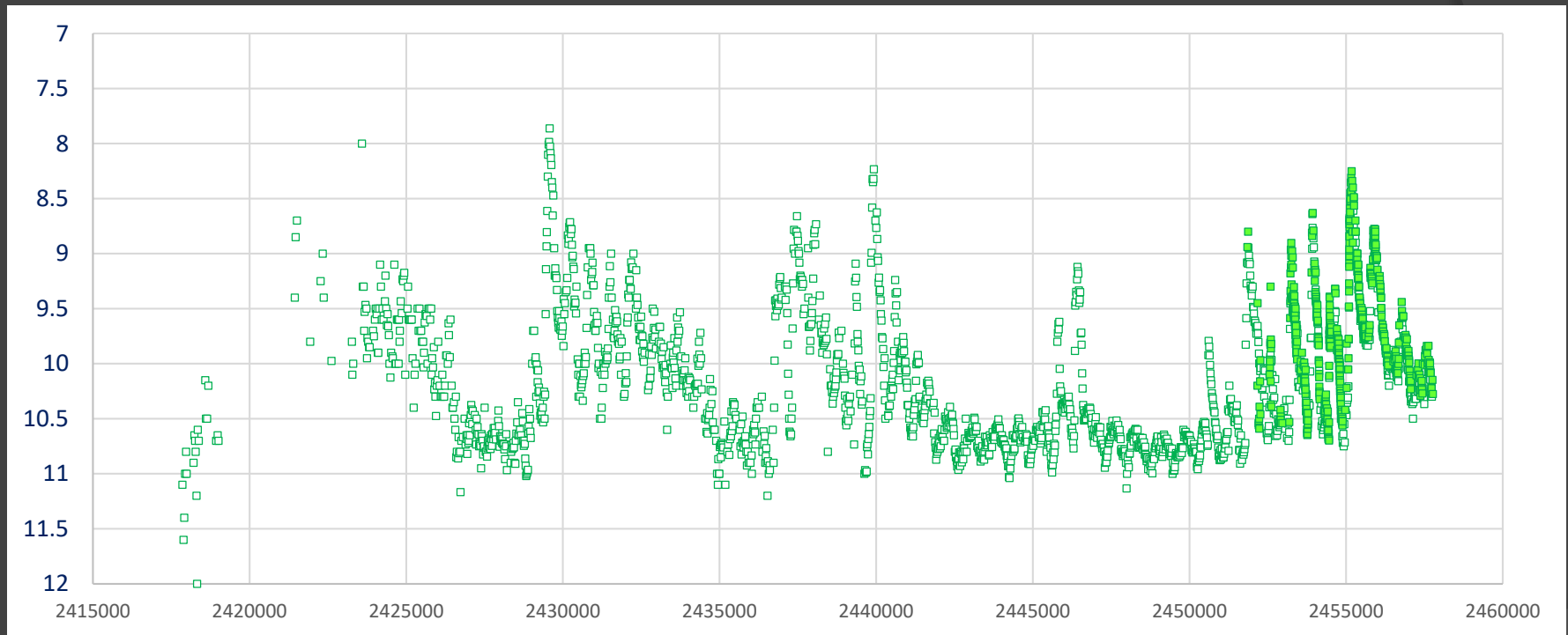
spectrograms. Thus Z Andromedae has become the prototype for those anomalous «symbiotic» stars in which high-excitation emission lines are superposed on a low-temperature absorption spectrum, usually of type M.



Etoiles symbiotiques

Z And
Prototype dans GCVS

Courbe de luminosité (Visible) – AAVSO – depuis 1907



Outburst (High state) - 1 à 3 magnitudes

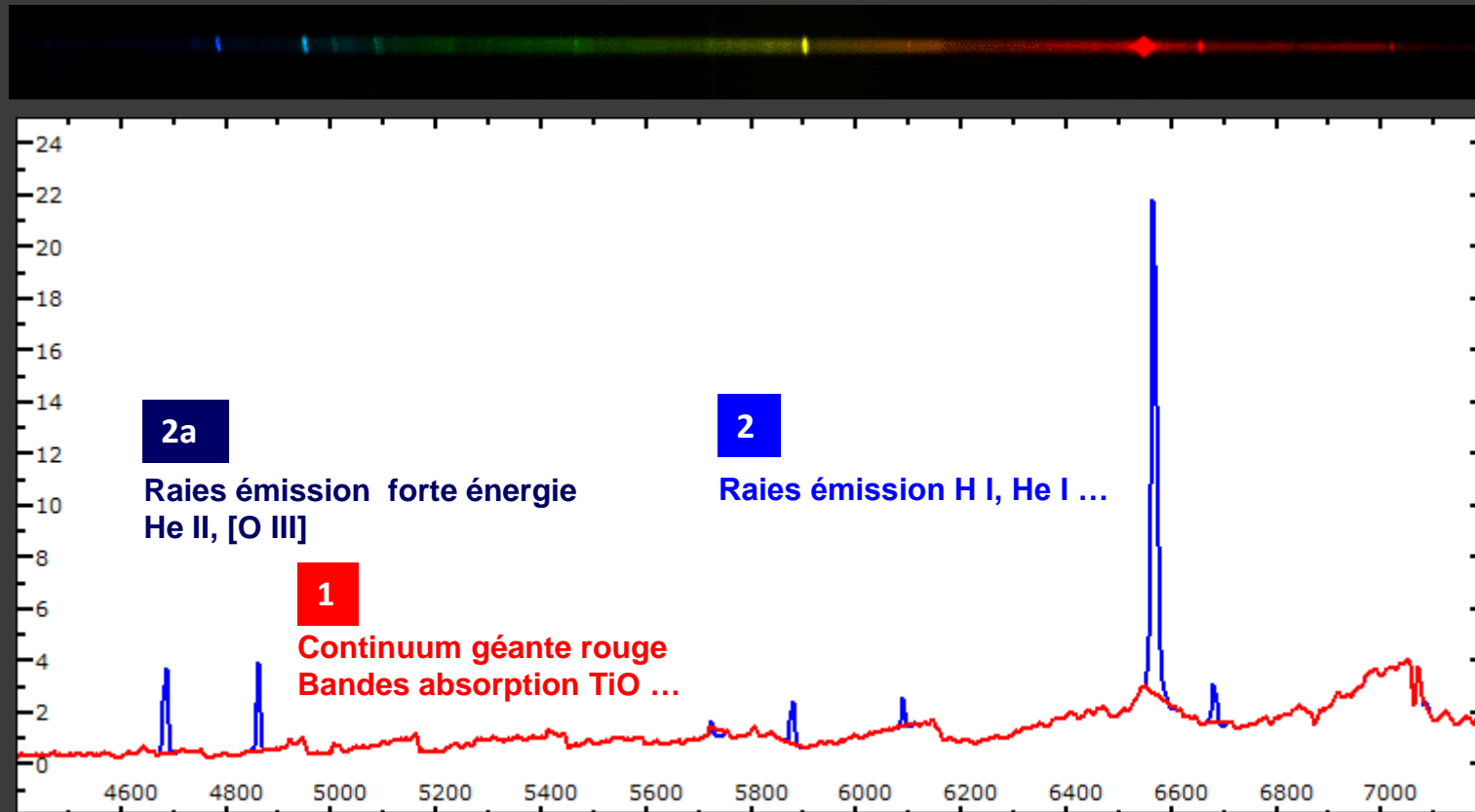
Etat calme (Quiescent state) – Variations orbitales

Etoiles symbiotiques : Définition

Belczinski & al., 2000

1. Présence de bandes d'absorption caractéristiques d'une géante de type tardif (late-type giant), parmi lesquelles TiO, H₂O, CO, CN, VO ainsi que des lignes d'absorption telles que CaI, CaII, FeI, NaI
2. Présence de fortes raies d'émission HI, HeI et ...
 - raies d'émission d'ions tels [OIII] (potentiel d'ionisation > 35 eV)
 - [...]

Caractéristique : Spectre composite



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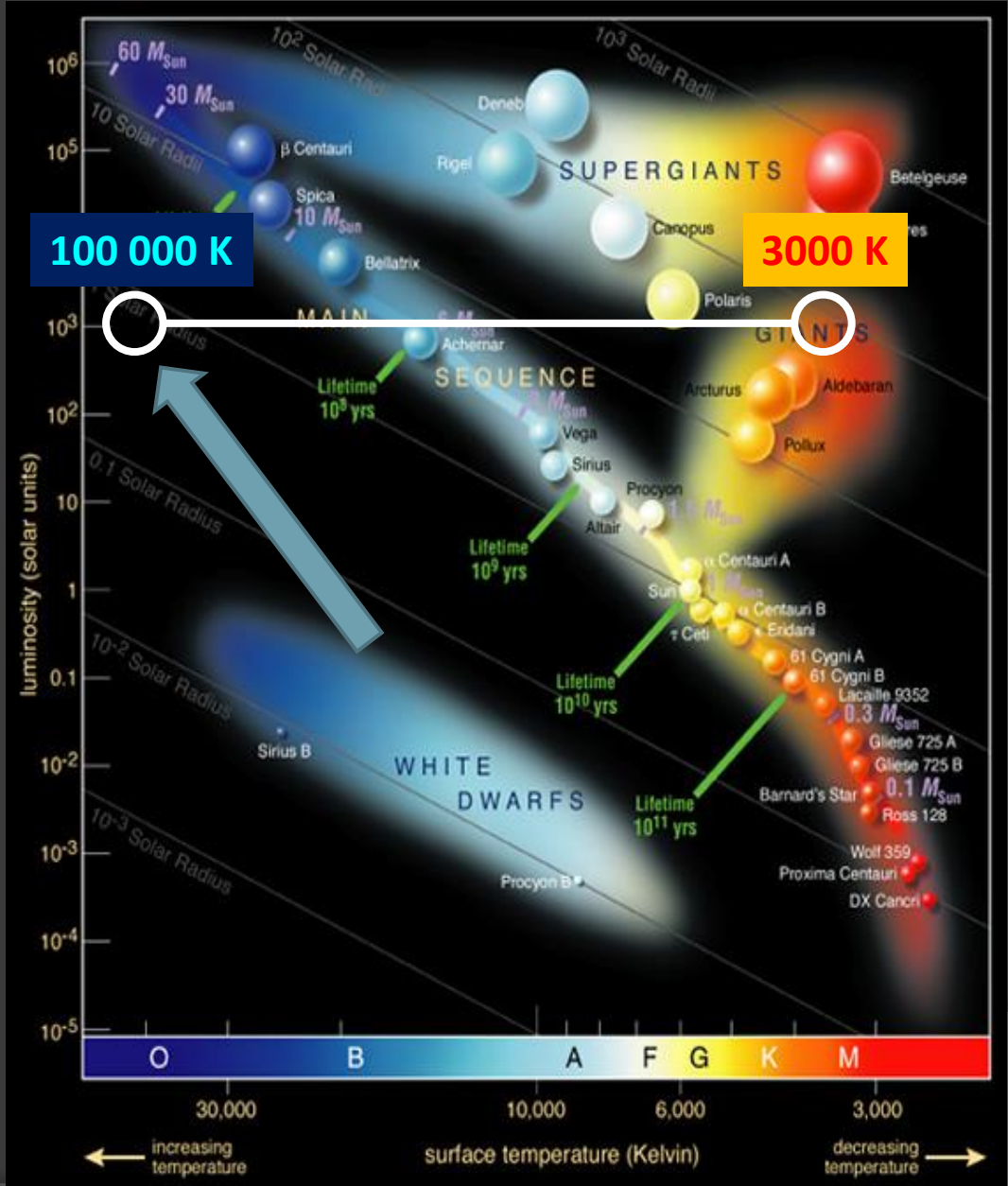
Etoiles symbiotiques : Etoiles binaires en interaction

'70 : abandon des modèles à étoile unique (FUV)

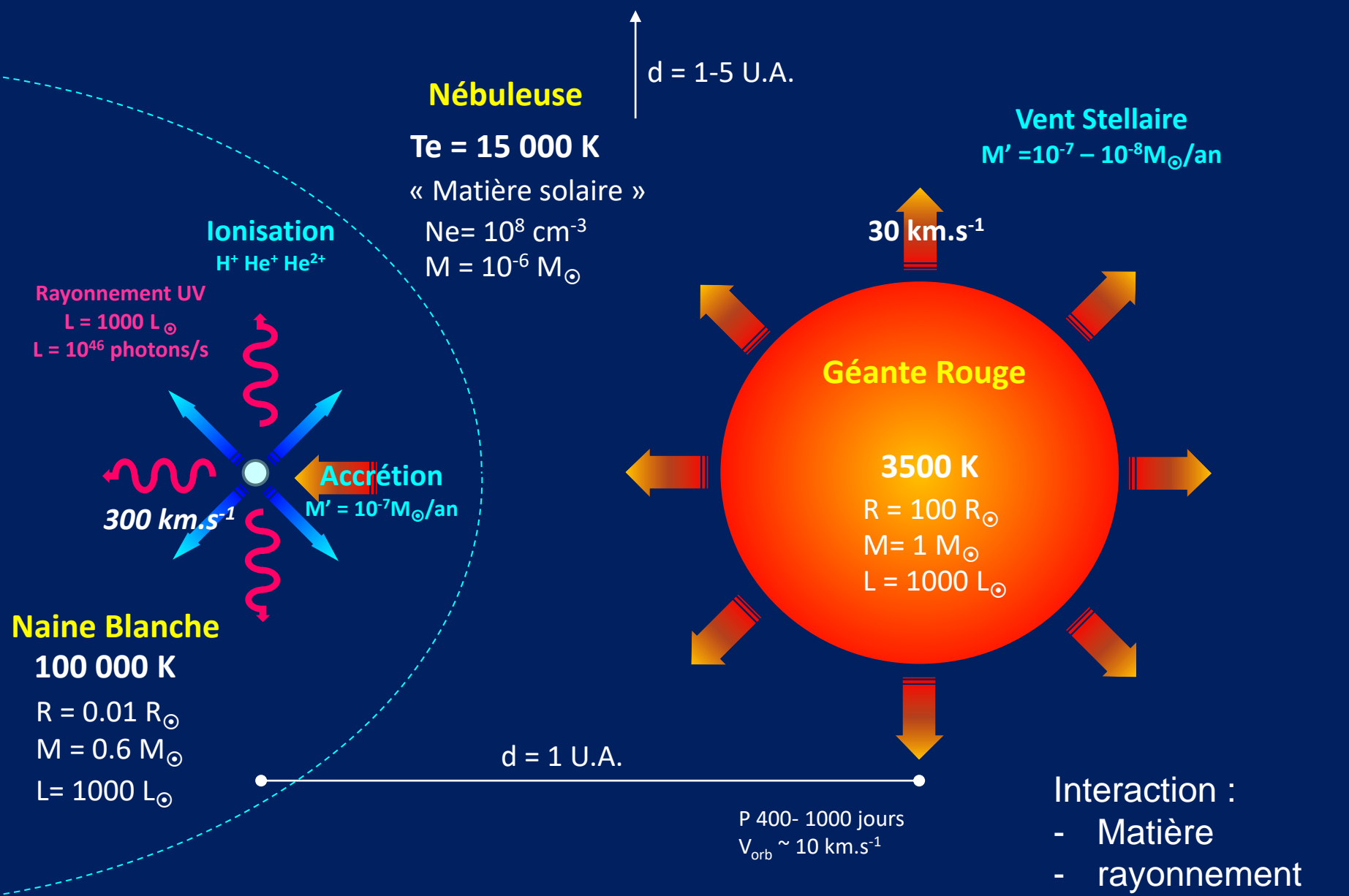
1000 L_☉

Symbiotiques

Systèmes binaires composés d'étoiles de forte luminosité dont les températures sont très différentes

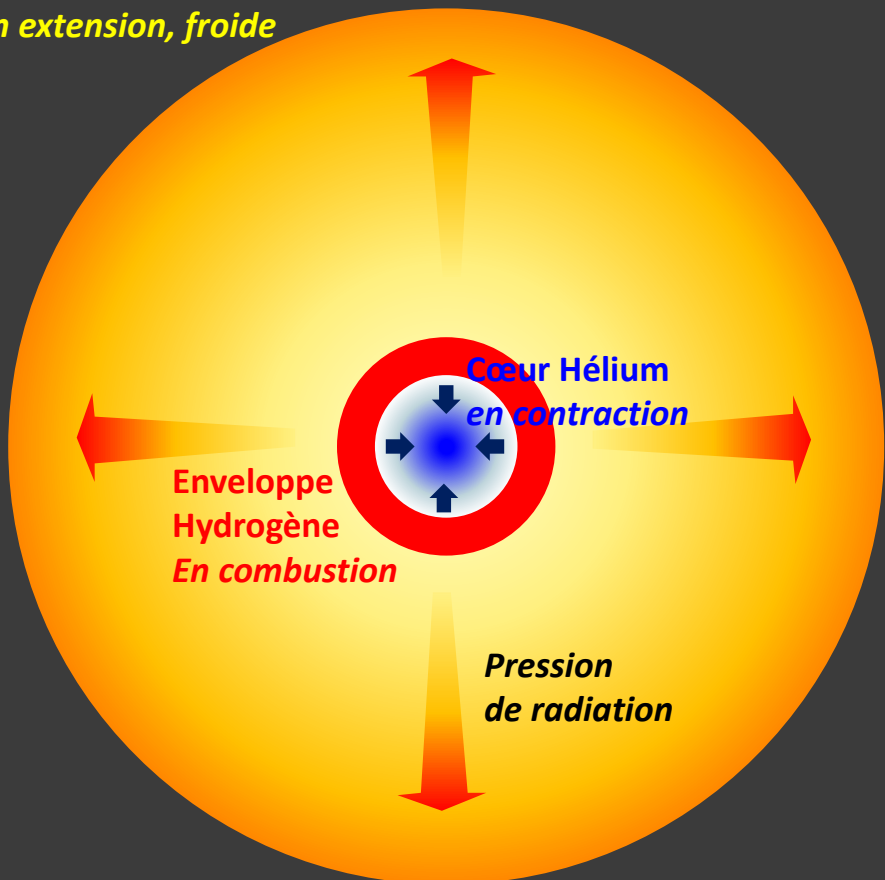


Modèle étoile symbiotique classique



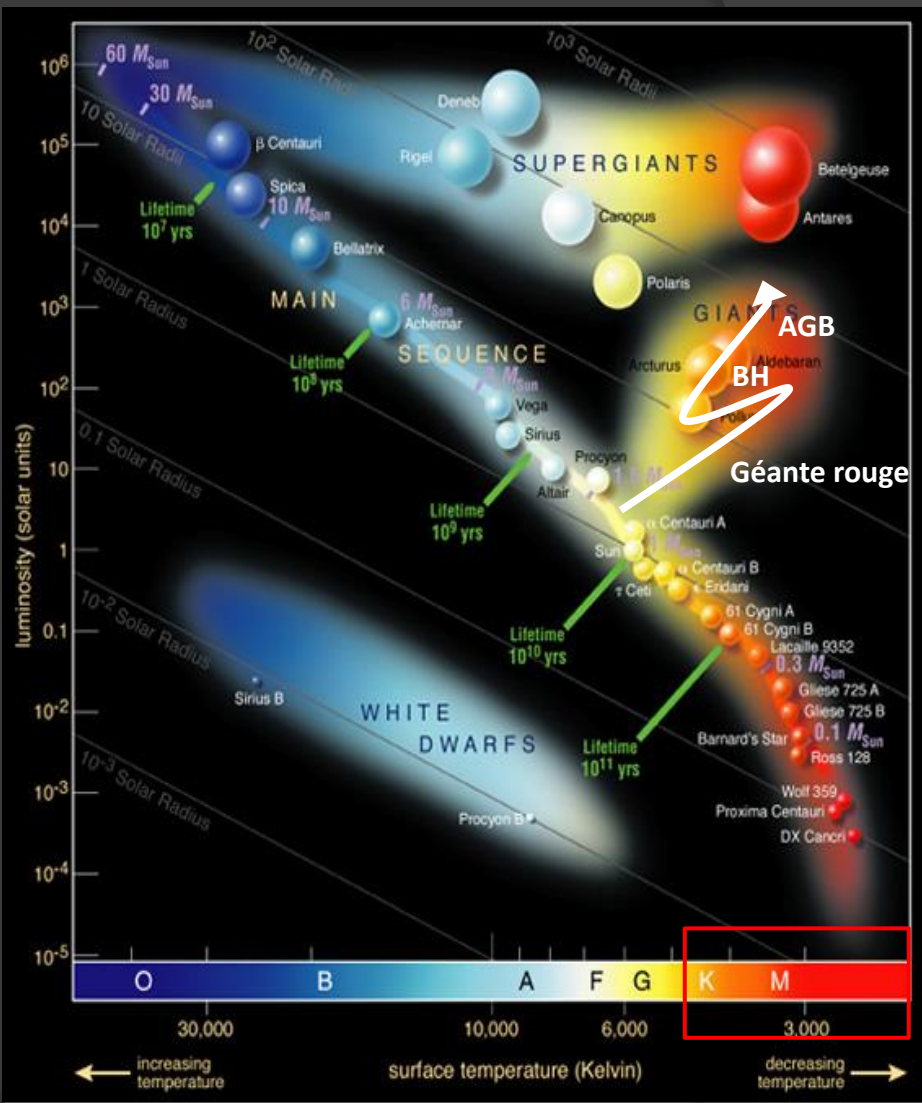
Géante Rouge

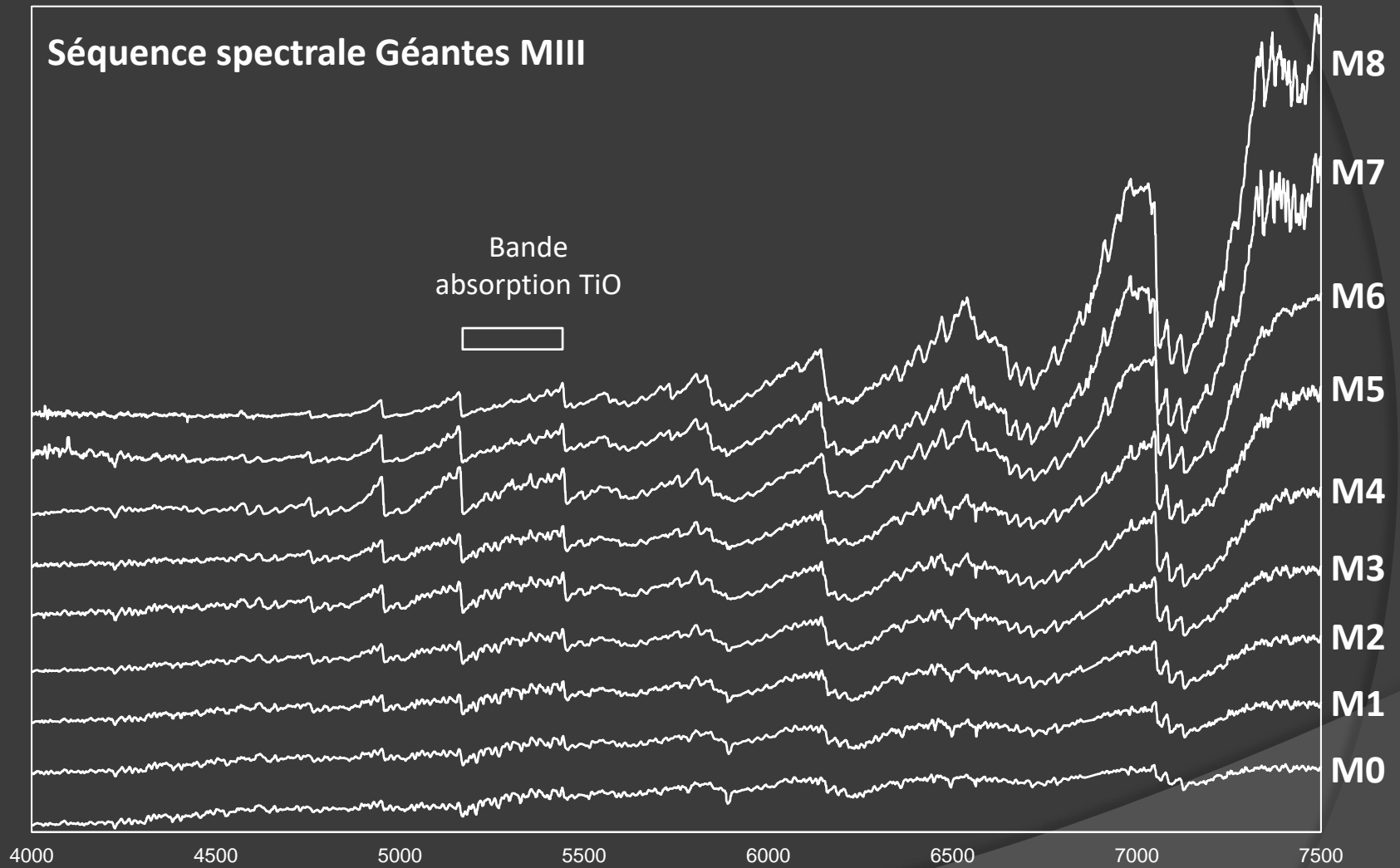
Enveloppe extérieure
Hydrogène
En extension, froide



10 – 100 R_{\odot}
1000 L_{\odot}
T 2300 – 3900 K

10% des étoiles du catalogue BSC



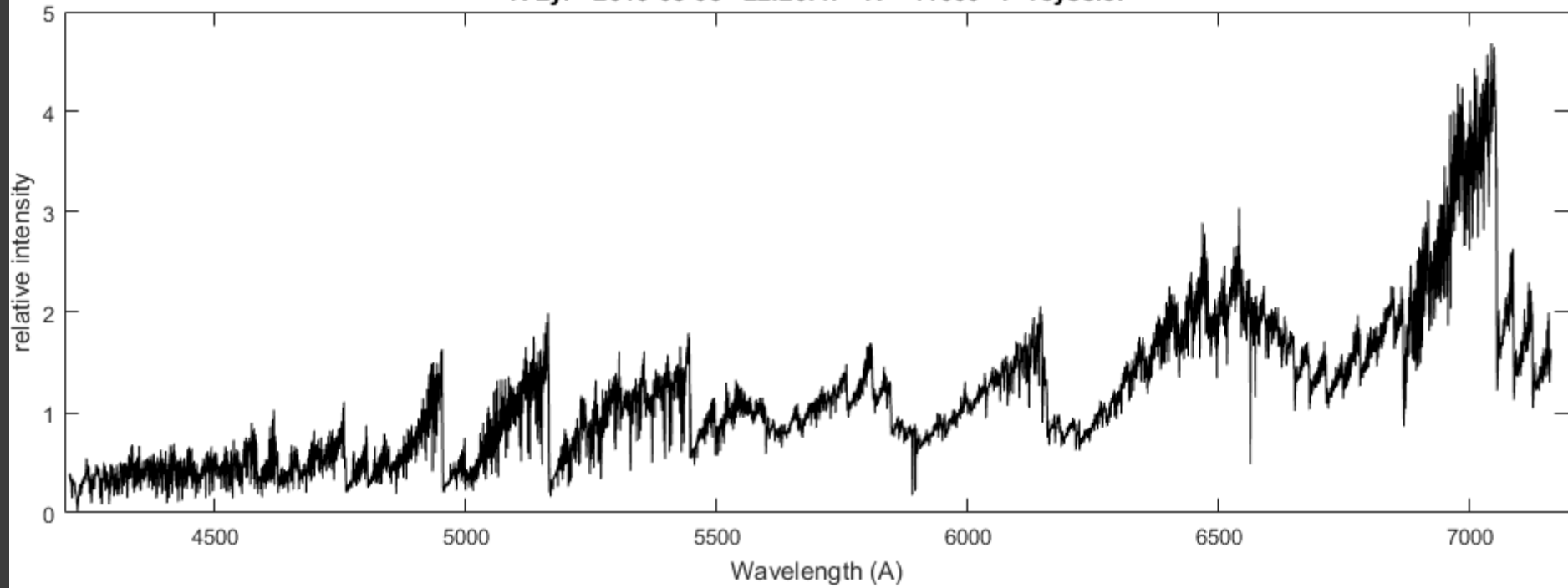


Géante Rouge

R Lyr

M5III

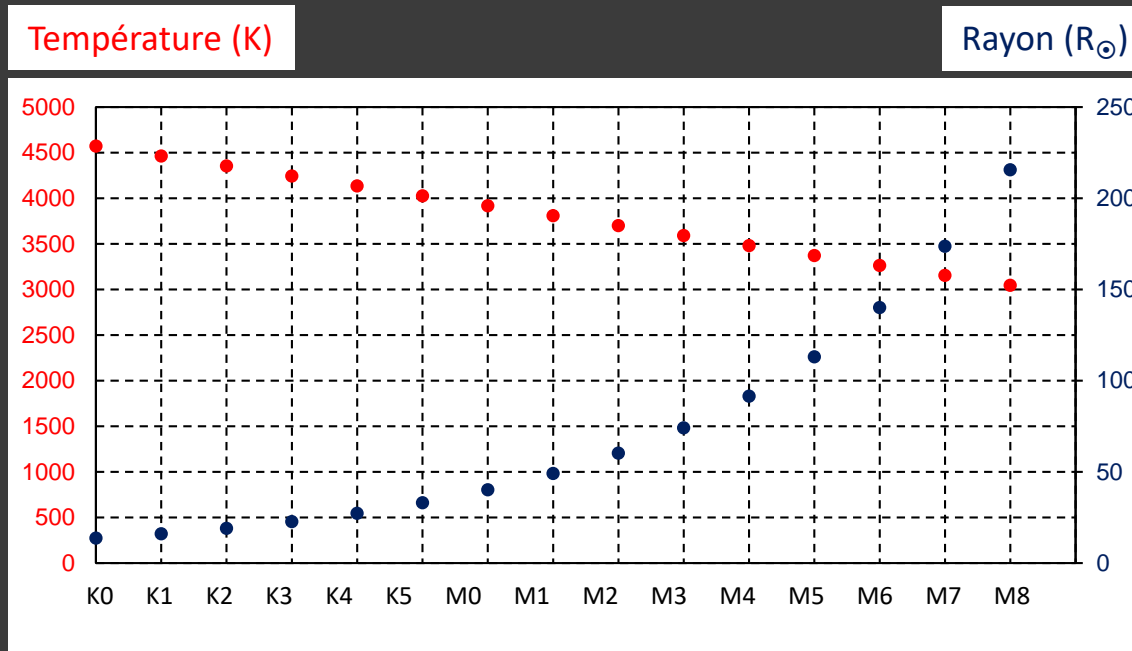
R Lyr 2016-08-05 22:20:47 R = 11000 F Teysier



Géante Rouge

Van Belle & al. (1999)

Mesures interférométriques du rayon de géantes et supergéantes rouge



Régressions :

Température $T = -109 \cdot ST + 4570 \text{ K}$

Rayon $R = 4.04 + 9.58 \cdot 10^{(0.096 \cdot ST)}$

ST = type spectral : K0 = 0 .. M8 = 14

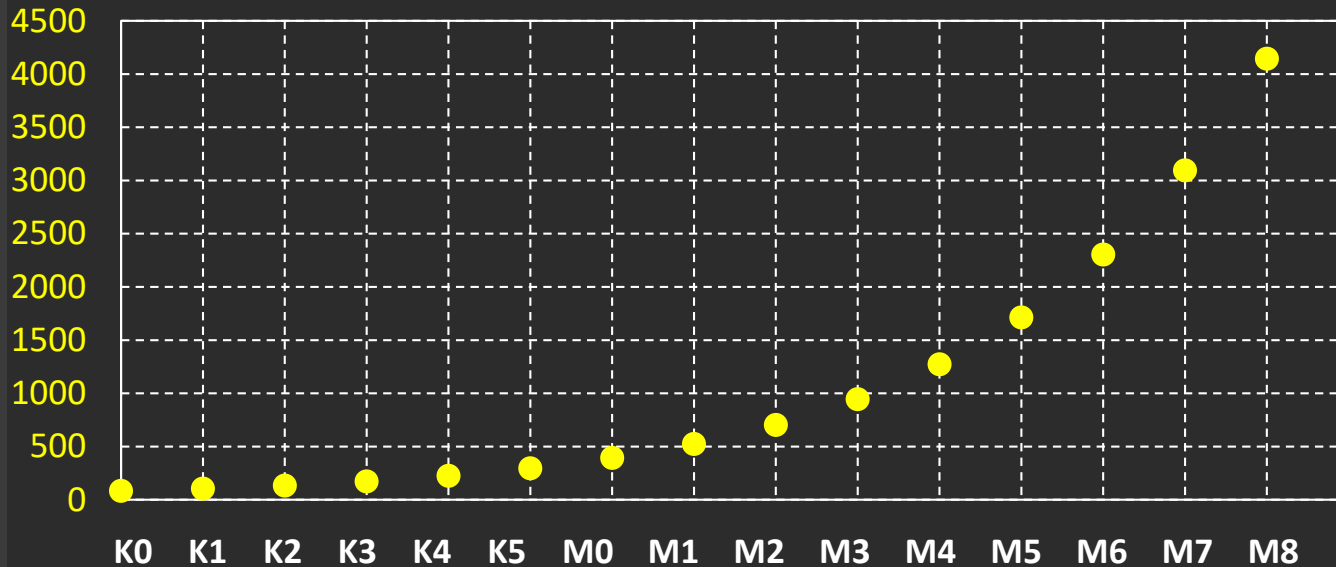
Luminosité en fonction du type spectral

$$L = 4 \pi R^2 \sigma T^4$$

σ : constante de Stefan-Boltzmann

$$L = (R/R_{\odot})^2 \sigma (T/5770)^4$$

Luminosité
[L_{\odot}]



R ↑ \Rightarrow L ↑
Forte Luminosité

Géante Rouge

Très faible gravité de surface

Perte de masse

Reimers (1975)

$$M' = 4 \cdot 10^{-13} \eta r ((L_* R_*) / (M_*))$$

ηr : 1/3 à 3 selon le type d'étoile

L_* R_* M_* exprimés en M_\odot

M' en M_\odot / an

$$L_* R_* / M_* \sim 100\,000$$

$$M' \sim 10^{-8} M_\odot / \text{an}$$

$$M' \sim 10^{22} \text{ kg} / \text{an}$$

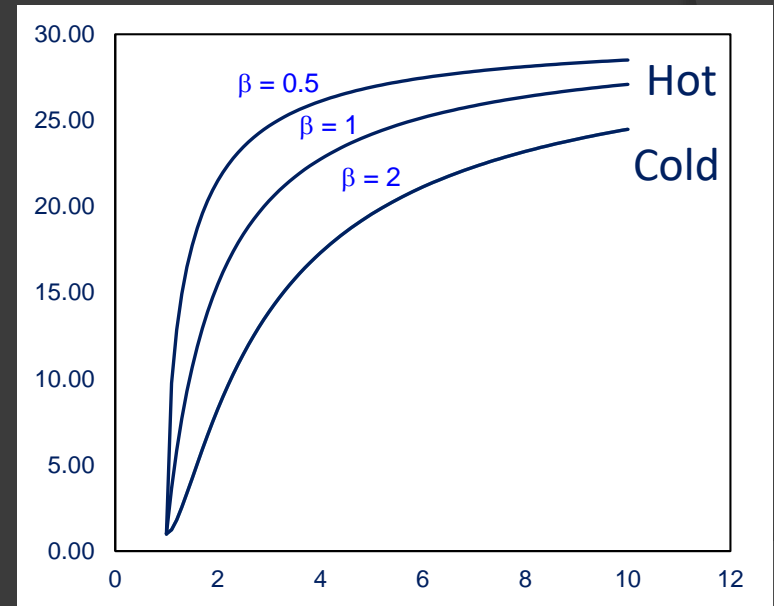
$$M' \sim 1/100 \text{ masse terrestre} / \text{an}$$

Vitesse du vent stellaire

Lamers & Cassinelli (1999)

$$v(r) \sim v_\infty ((1 - R_*)/r)^\beta$$

v ($\text{km} \cdot \text{s}^{-1}$)



Distance r en R^*

V_r = vitesse à la distance r exprimée en rayons de l'étoile

V_∞ = vitesse maximale (asymptotique)

R^* = rayon de l'étoile

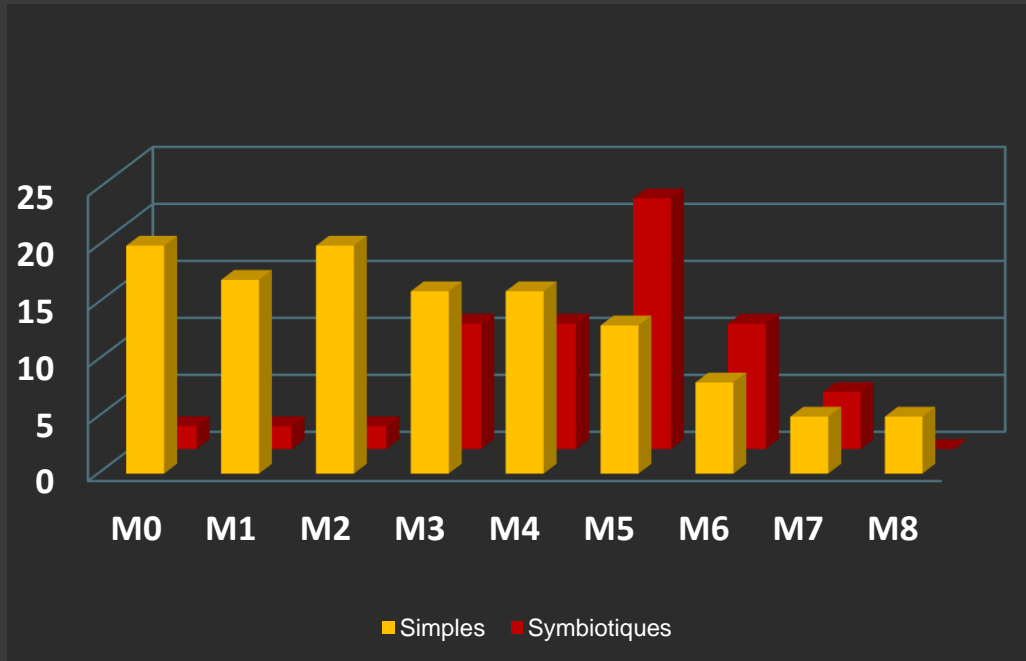
β = facteur dépendant du type étoile

Géante Rouge

Distribution du type spectral

Géante rouge des symbiotique de type plus tardif
= condition du phénomène symbiotique

→ Perte de masse plus élevée



[Mürset & Schmid, 1999]

Keyes 2004

AG Dra	< K4
AG Peg	M1.7 III
EG And	M2.4 III
BF Cyg	M4.2 III
T CrB	M4.4 Ib-II
Z And	M4.4 III
AX Per	M4.8 III
CI Cyg	M4.8 III
V443 Her	M4.9 III

Classification Spectrale

Etoile froide

Keyes 2004

Mürset 1999

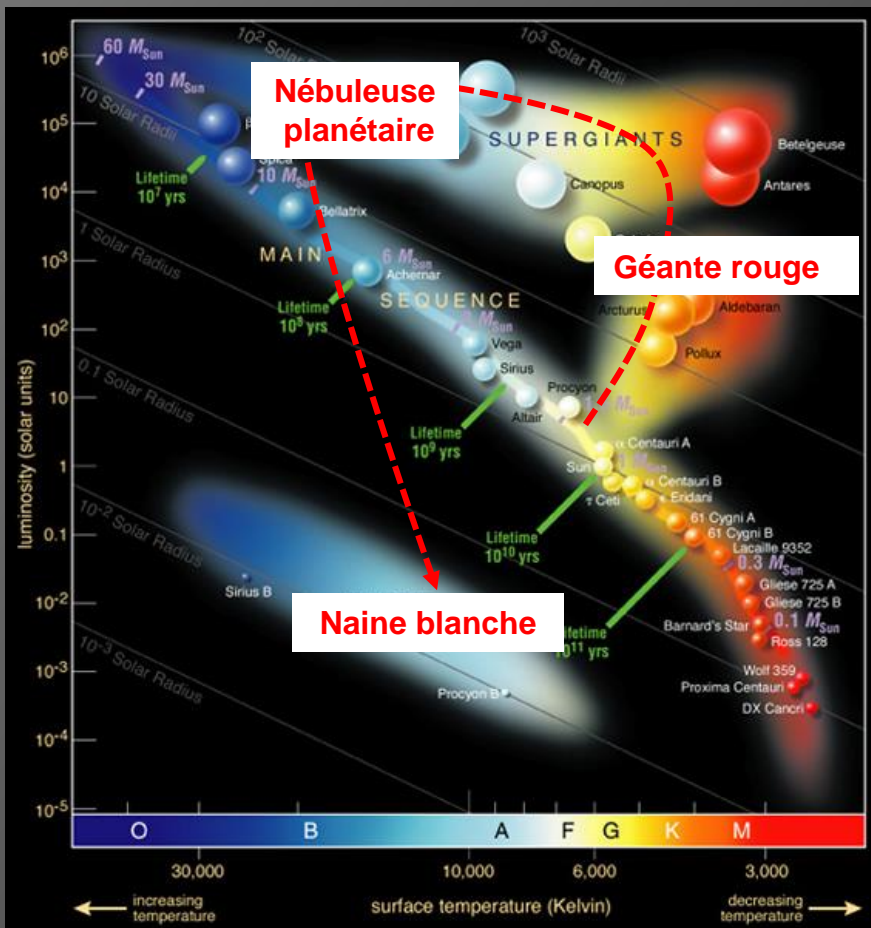
Kenyon 1987

Naine blanche

Stade ultime de l'évolution des étoiles
de masse $< 10 M_{\odot}$

Absence de réactions thermonucléaires
Matière condensée
En refroidissement ($100\,000\text{ K} \rightarrow$)

Plusieurs types en fonction
de la masse initiale de l'étoile



Type	Principaux constituants	Masse initiale	Masse finale
C O	Carbone Oxygène	$< 9 M_{\odot}$	$< 1.1 M_{\odot}$
O Ne	Oxygène Néon	$9 M_{\odot} < M < 11 M_{\odot}$	$< 1.4 M_{\odot}$
He	Hélium		

Valeurs approximatives
Voir Doherty & al., 2010

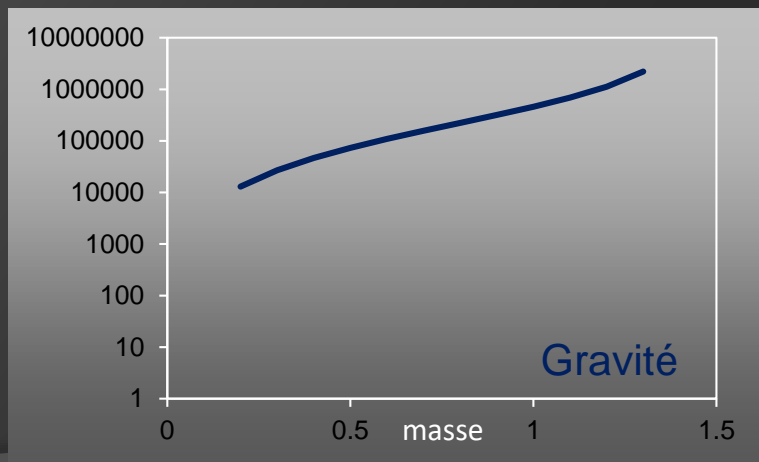
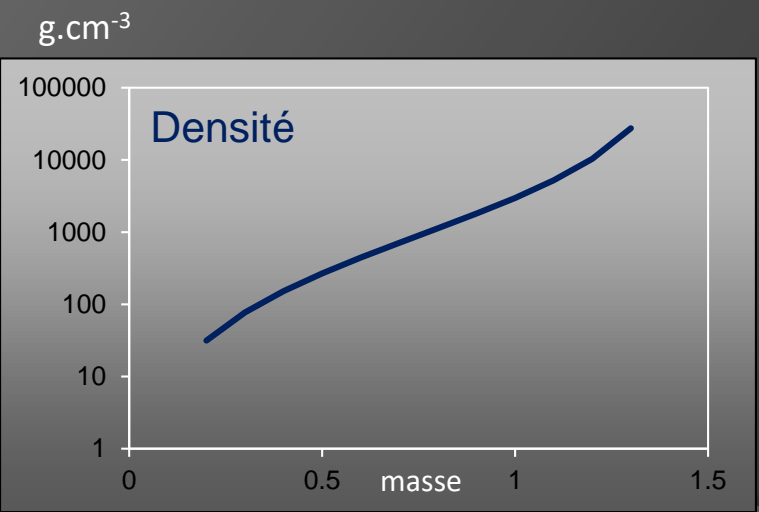
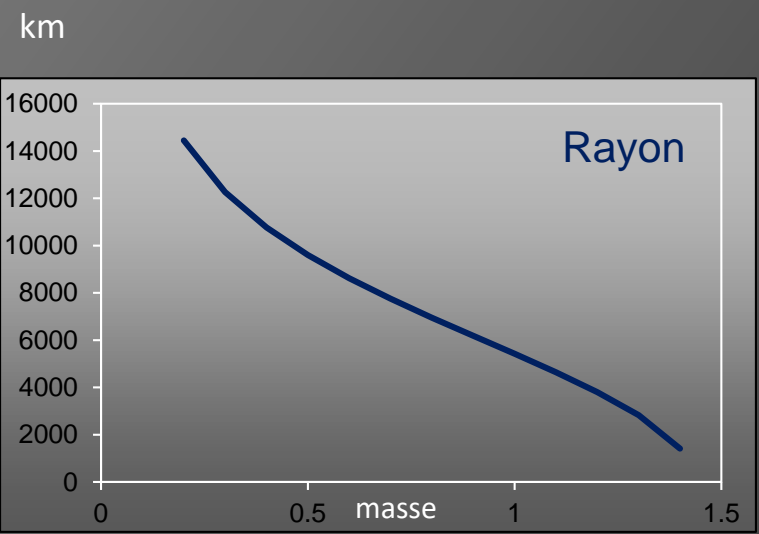
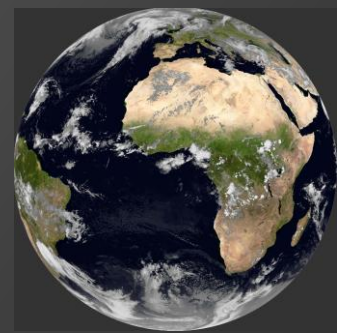
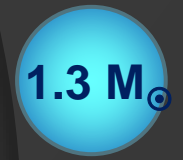
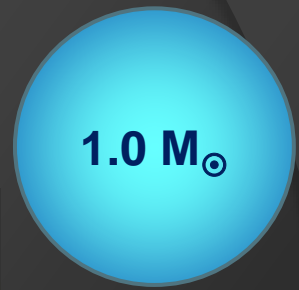
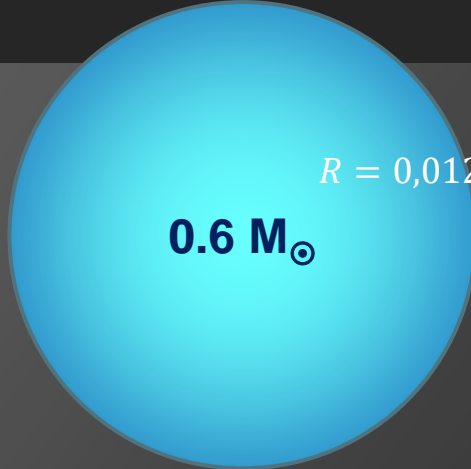
Masse moyenne = $0,6 M_{\odot}$

Si $M > 1,4 M_{\odot}$: effondrement de type supernova Ia
(limite de Chandrasekar)

Naine Blanche

Naines blanches

$$R = 0,0126 \times \left(\frac{2}{M_e}\right) \times M^{-\frac{1}{3}} \times \left[1 - \left(\frac{M}{M_{Ch}}\right)^{\frac{4}{3}}\right]^{-\frac{1}{2}}$$

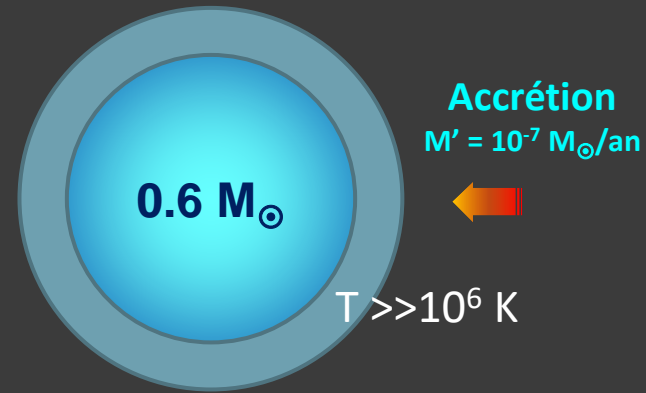


Quelques grandeurs caractéristiques en fonction de la masse de la naine blanche exprimée en masses solaires

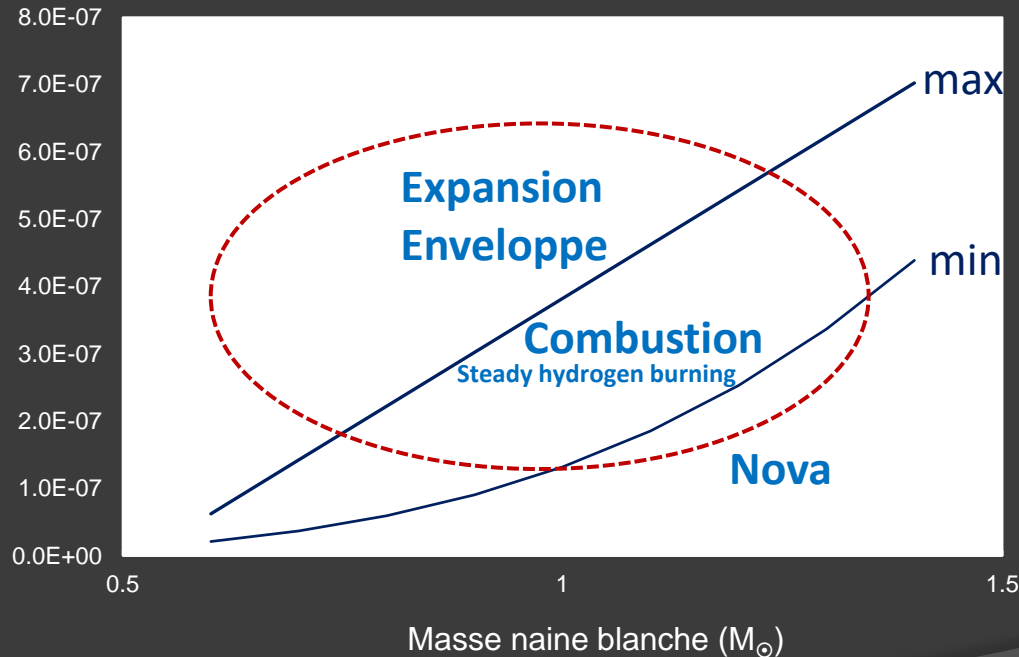
Naine Blanche

Réactions thermonucléaires stables dans l'enveloppe de matière non dégénérée

(Novae : réactions explosives
dans une enveloppe dégénérée
avec éjection d'une partie de l'enveloppe)



Accrétion (M_⊙/an)



Taux d'accrétion minimum:
Iben, 2002
 $M' = 1,32 \cdot 10^{-7} M_{\odot}/\text{an} \cdot M_{\text{wd}}^{3.57}$

Taux d'accrétion maximum
Paczynski, 1970
 $\text{Max} = 8 \cdot 10^{-7} M_{\odot}/\text{an} \cdot (M_{\text{wd}} - 0,522 M_{\odot})$

Note : modèles simples
Luminosité, Twd

Composant chaud : Naine blanche + Enveloppe

Forte dispersion

	T [K]	R [R_{\odot}]	L [L_{\odot}]	Date
EG And	70 000	0.02	7.5	Oct. 82
AX Per	105 000	0.08	710	Oct. 84
AG Dra	130 000	0.01	19	Jun. 83
CI Cyg	115 000	0.06	560	Aug. 83
Z And	130 000	0.08	1600	Sep. 84
YY Her	100 000	0.11	1100	Aug. 80

Faible luminosité :
Accrétion seule
(Energie gravitationnelle)
Forte Luminosité :
Réactions thermonucléaires

Mürset 1991

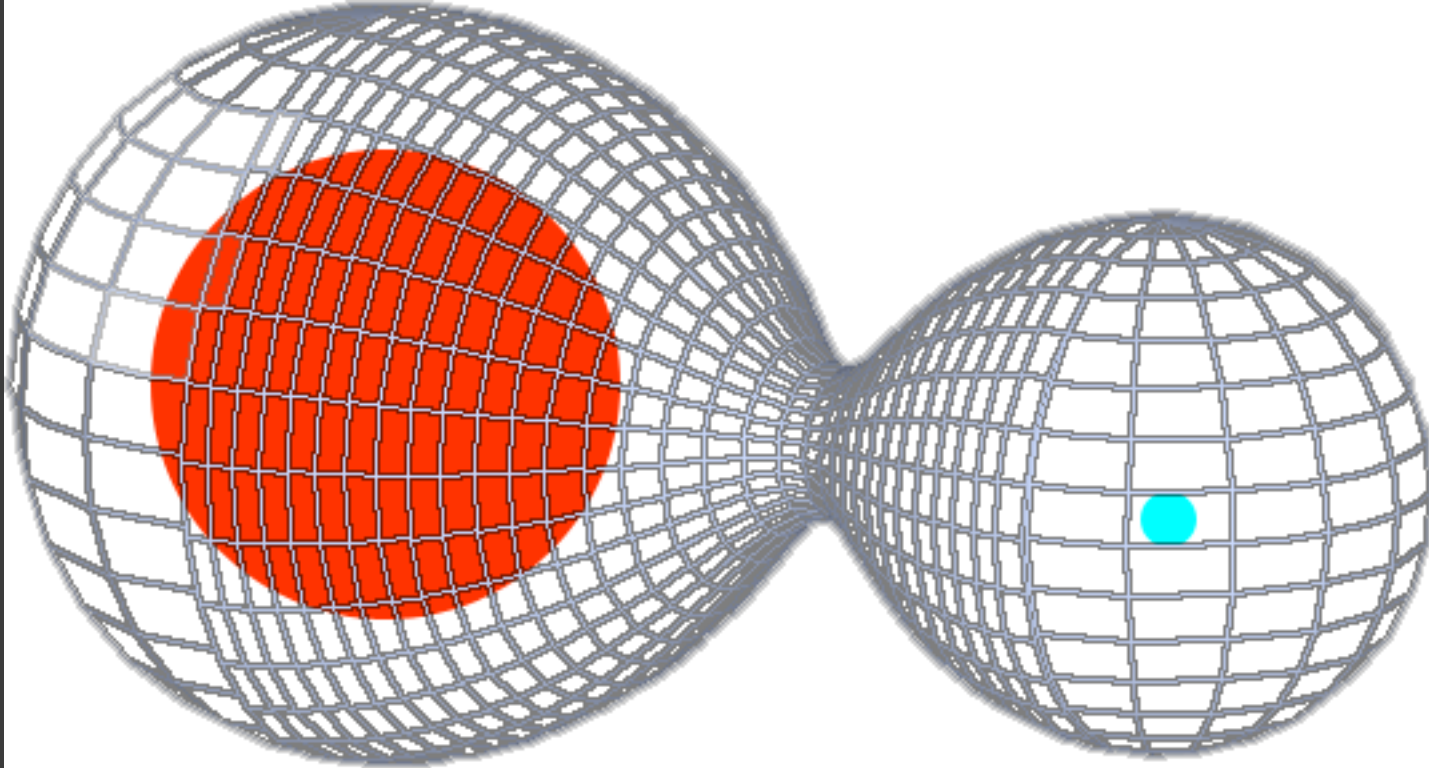
Variabilité importante

Z And

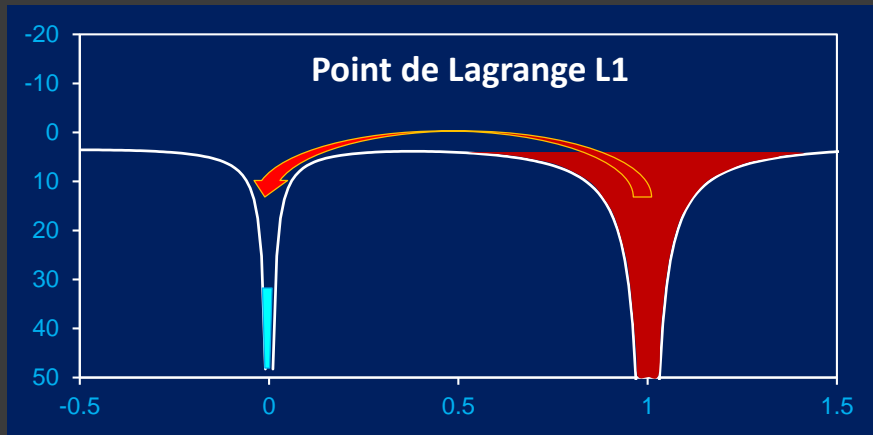
T [K]	L [L_{\odot}]	Date
110 000	620	07-79
105 000	620	05-80
110 000	860	08-80
105 000	720	01-81
130 000	1600	09-84
125 000	1600	10-84

Lobes de Roche

$$M_1/M_2 = 2$$



Taux d'accrétion à la surface de la naine blanche



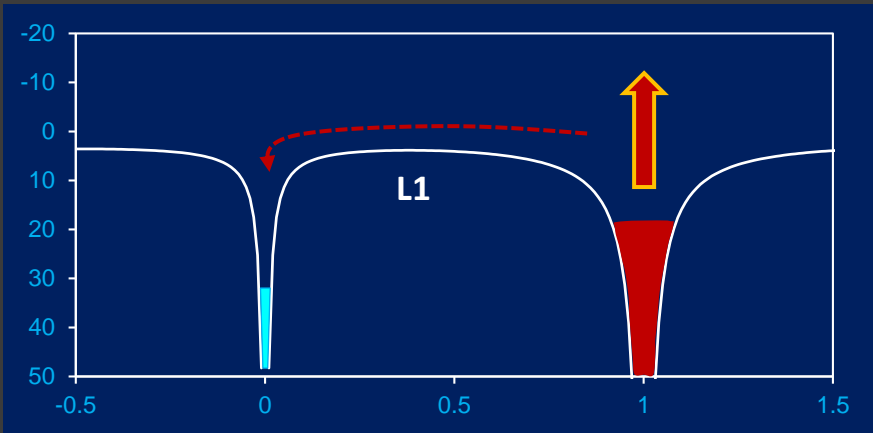
Naine Blanche
 $M = 0.6 M_{\odot}$

Géante rouge
 $M = 1 M_{\odot}$

Etoile rouge remplit son lobe de Roche

Accrétion \sim Perte de masse de la géante

En règle générale : ce n'est pas le cas des symbiotiques
Photométrie : variations ellipsoïdales



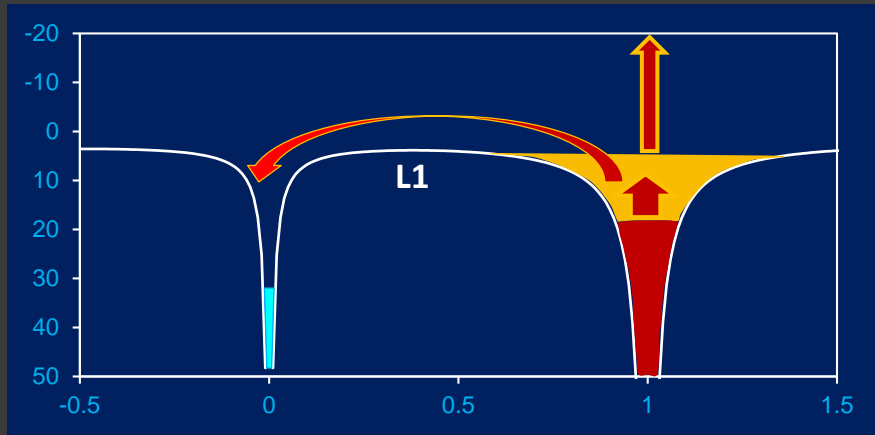
Etoile rouge ne remplit pas son lobe de Roche

Accrétion \sim 1-10 % de la Perte de masse de la géante

[Bondi & Hoyle]

Insuffisant pour maintenir la combustion de la matière
accrétée dans l'enveloppe de la naine blanche

Taux d'accrétion à la surface de la naine blanche



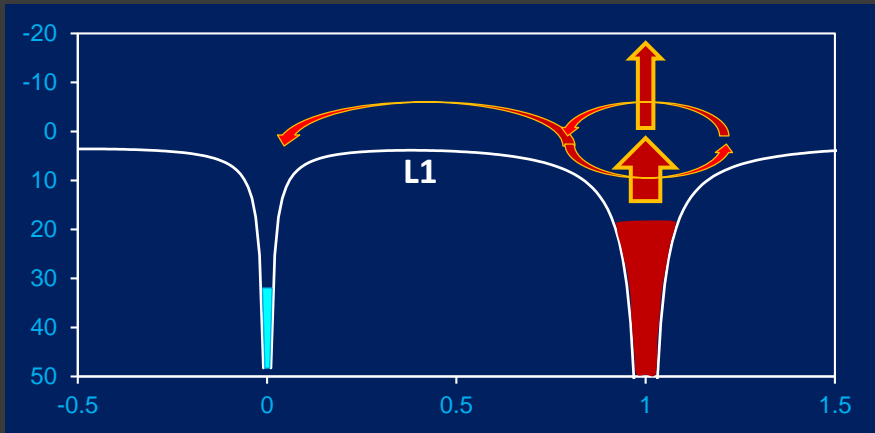
Naine Blanche
 $M = 0.6 M_{\odot}$

Géante rouge
 $M = 0.6 M_{\odot}$

Deux modèles

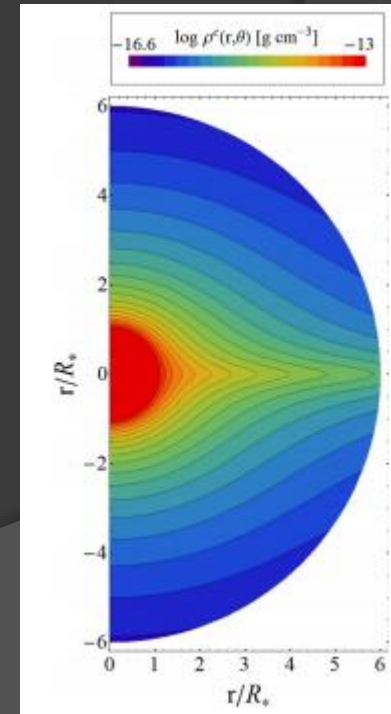
Le vent émis par la Géante Rouge est canalisé par le lobe de Roche

**Wind Roche-lobe overflow
WRLOF**



**Wind Compression Model
WCM**

La rotation de la géante produit une compression du vent



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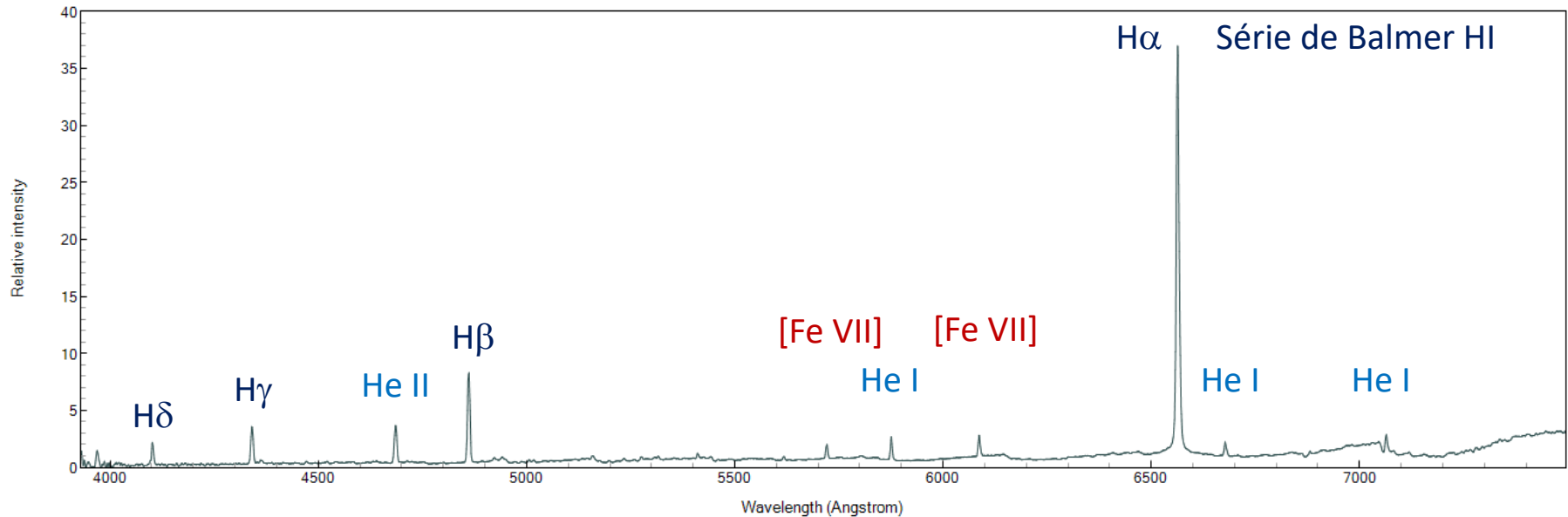
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Spectre typique Symbiotique classique

Cl Cyg 2011-08-28.859 François Teyssier



Raies « permises » Recombinaison après ionisation par radiations UV

Raies « interdites » Excitées par collision avec électrons libres

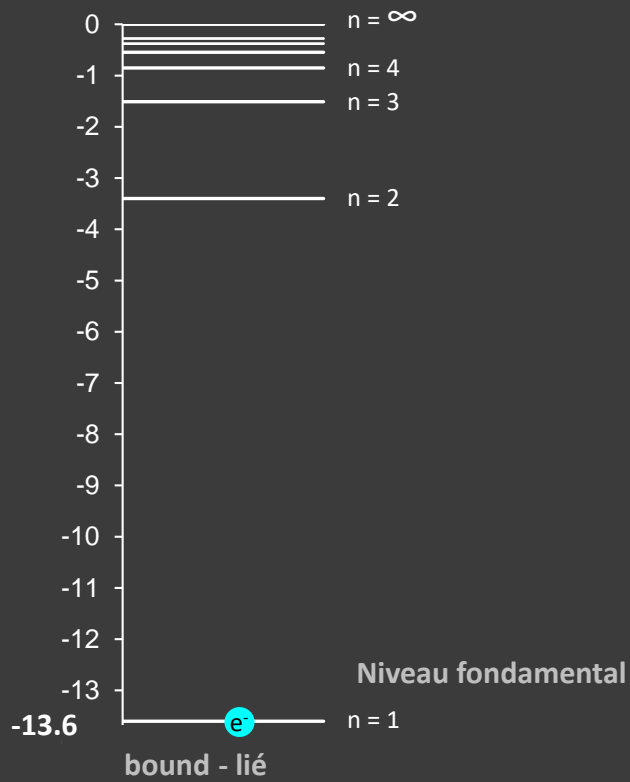
H

I.P. = 13.6 eV

Etat fondamental

$$E_n = -13.6 \text{ eV} / n^2$$

E [eV]



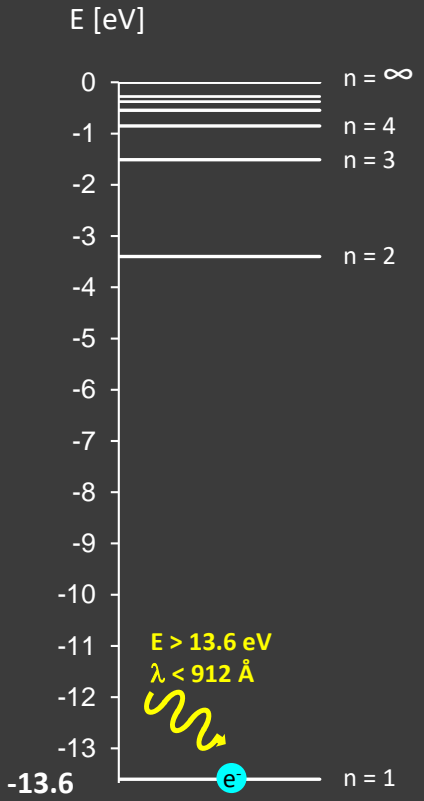
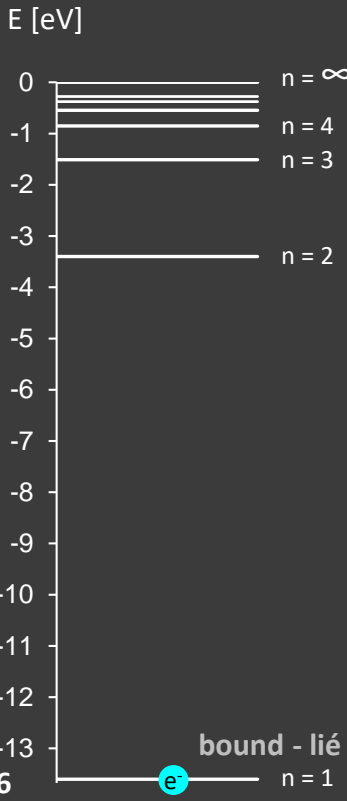
H⁺

Etat fondamental

$$E_n = -13.6 \text{ eV} / n^2$$

Ionisation $H \rightarrow H^+ + e^-$

free - libre



H^+

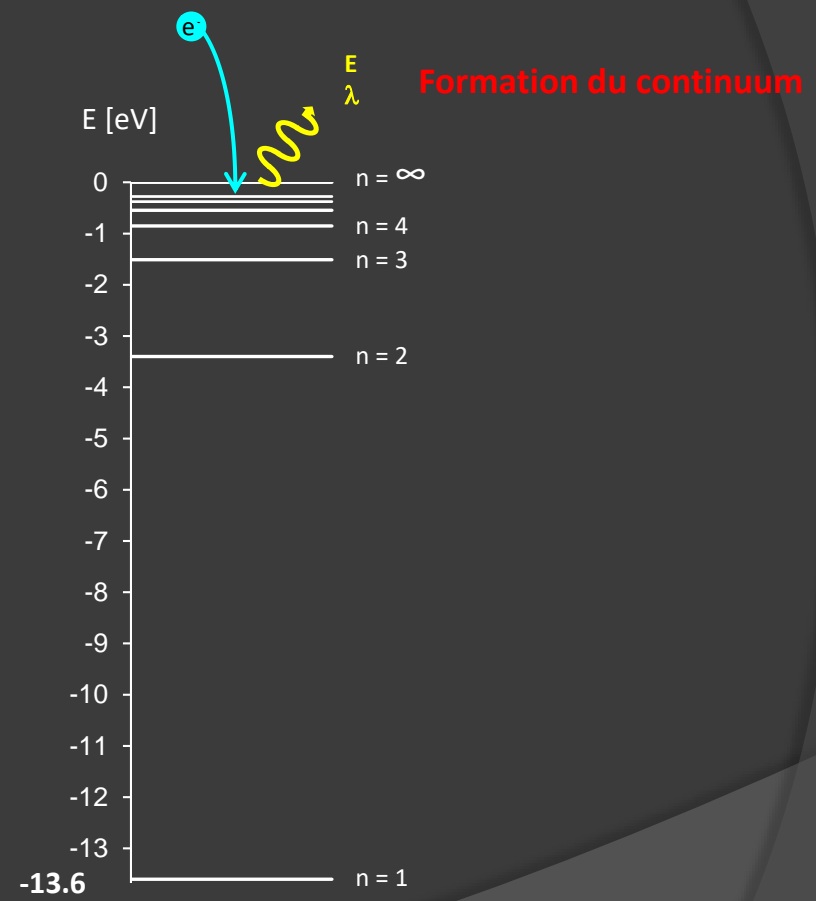
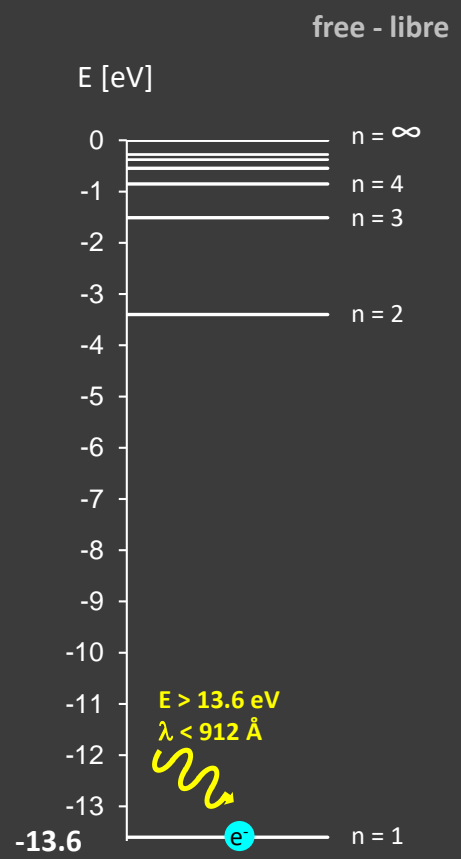
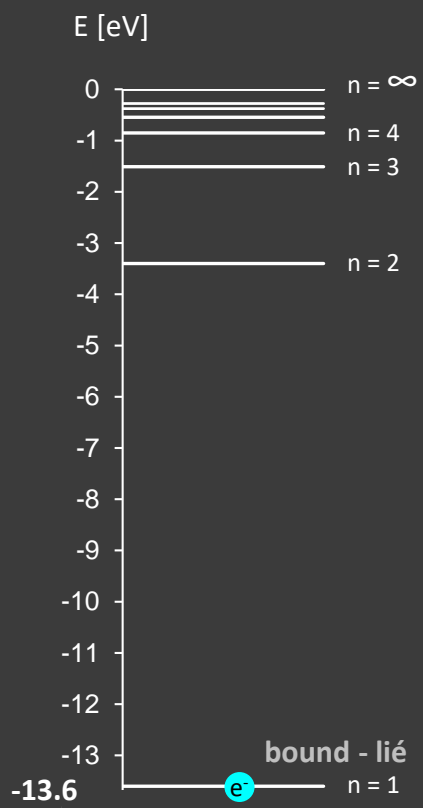
H^+

Etat fondamental

$$E_n = -13.6 \text{ eV} / n^2$$

Ionisation $H \rightarrow H^+ + e^-$

Recombinaison $H^+ + e^- \rightarrow H$



H^+

H^+

H^+

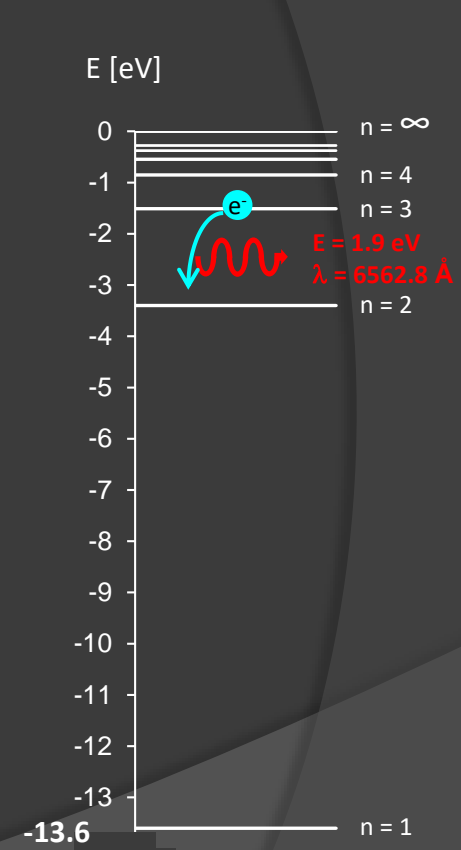
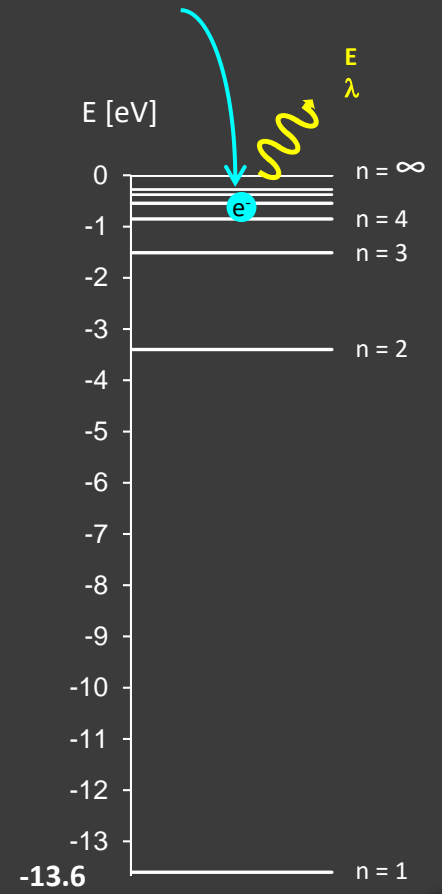
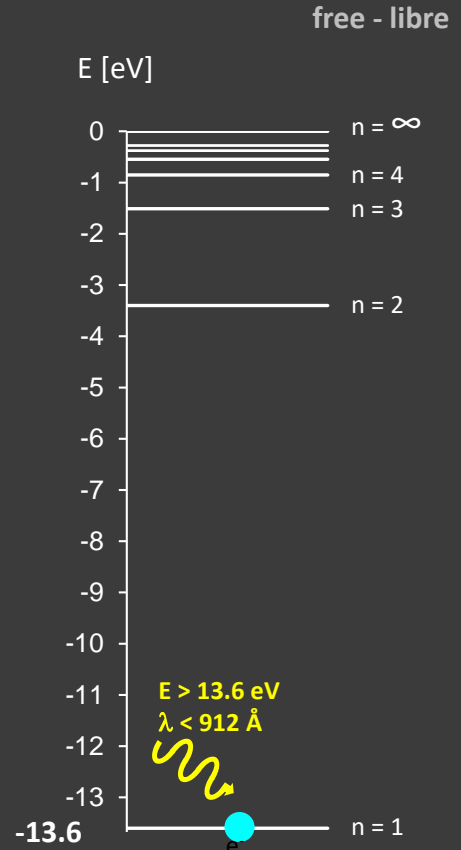
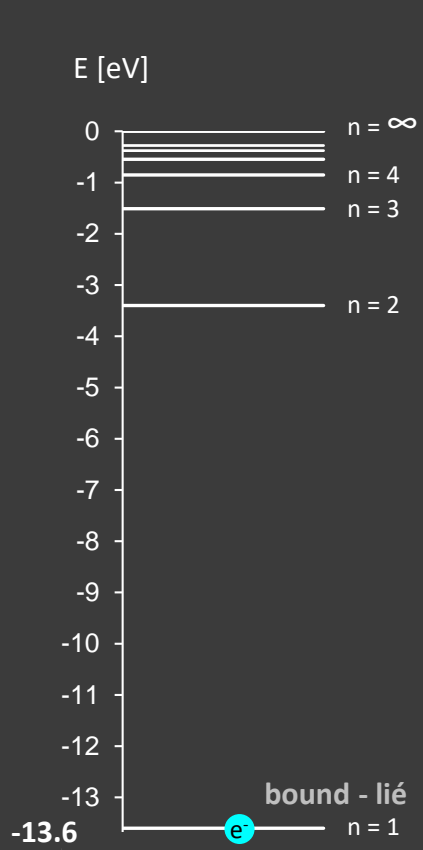
Etat fondamental

$$E_n = -13.6 \text{ eV} / n^2$$

Ionisation $H \rightarrow H^+ + e^-$

Recombinaison $H^+ + e^- \rightarrow H$

Cascade

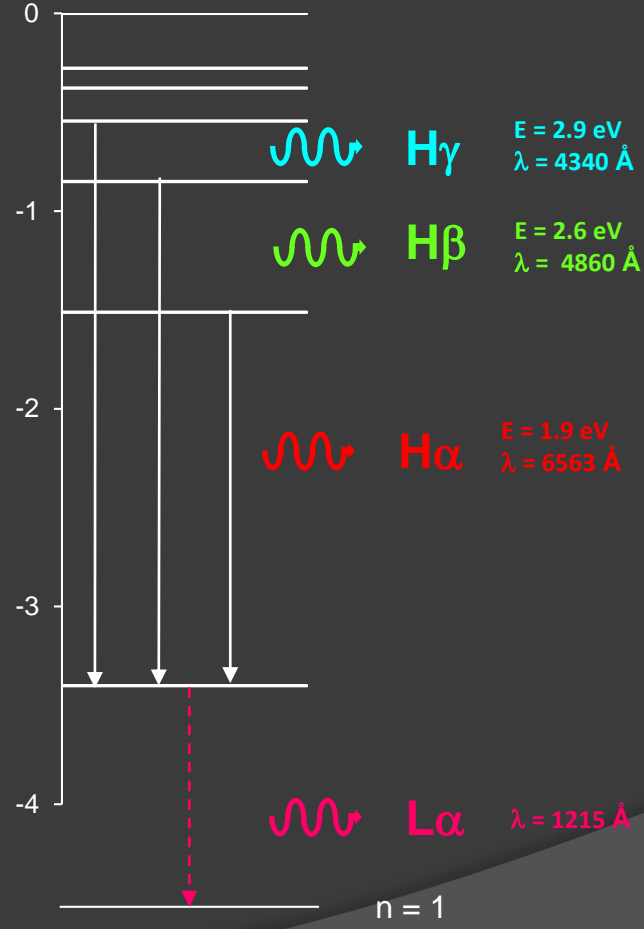
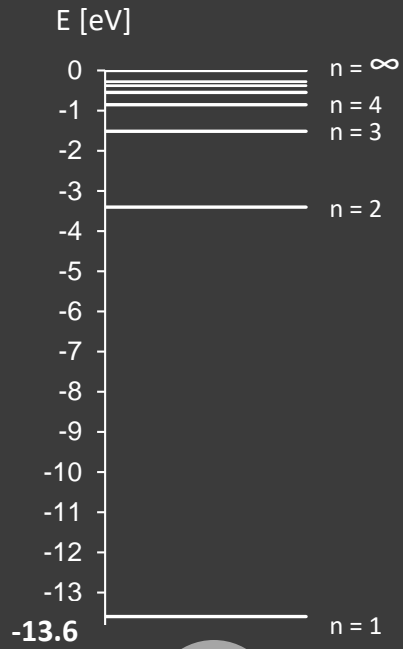


- Durée très courte de présence sur chaque niveau excité (10^{-8} s)
- Cascade de transitions produisant chacune un photon
- Atome dans son état fondamental ($n=1$)

Les photons émis dans le domaine « visible » du spectre sont ceux qui arrivent sur le niveau 2 = Série de Balmer (6563 à 3 Å)

Energie ionisation = 13.6 eV

$$E_n = -13.6 \text{ eV} / n^2$$



Epaisseur Optique
Longueur onde
Composition
Densité
Distance

$\tau \sim 1$
Emission

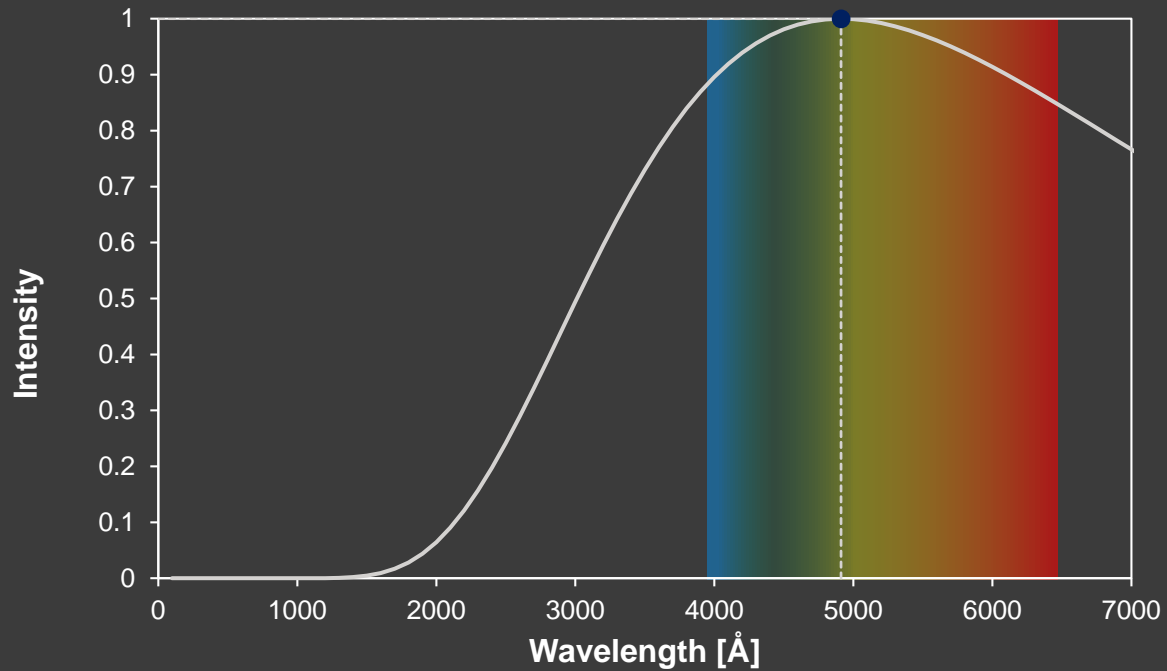
$\tau > 1$
Absorption





Microsoft Excel
Macro-Enabled Worksheet

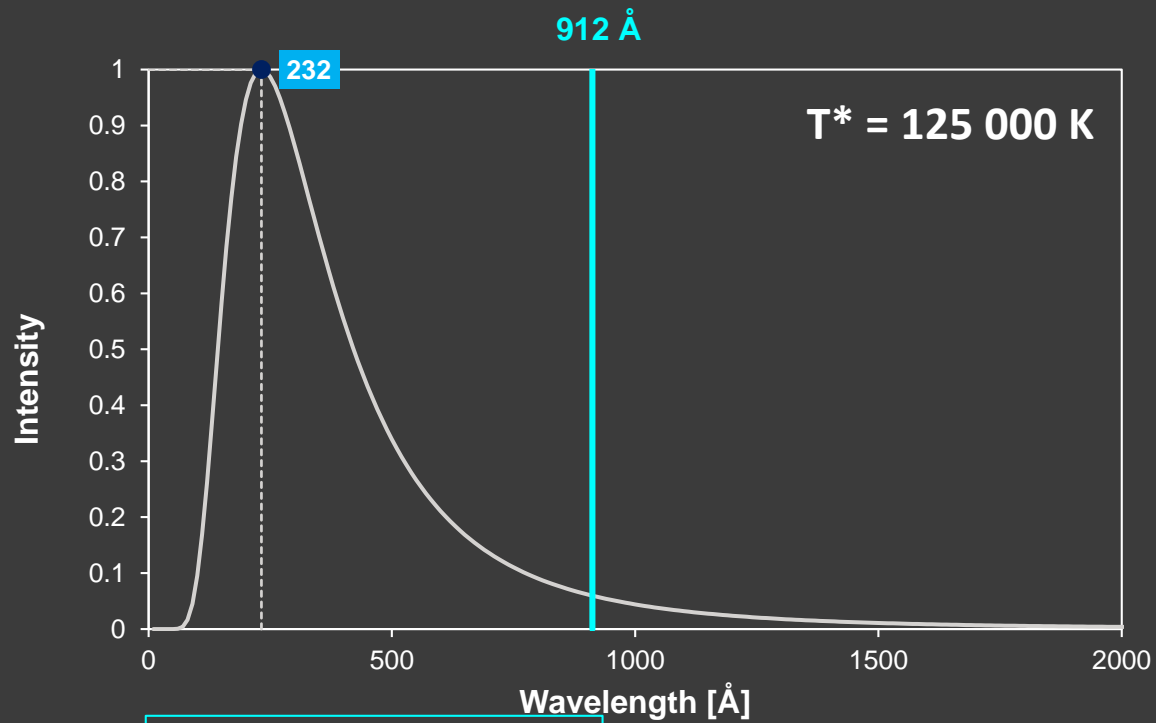
Planck : distribution d'énergie émise par un corps noir





Microsoft Excel
ro-Enabled Worksl

Planck : distribution d'énergie émise par un corps noir

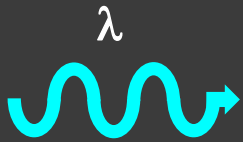


Photons ayant un énergie
suffisante pour ioniser H

Photoionisation

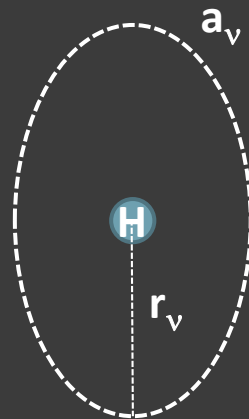
Proportion atomes ionisés par unité de volume

Nombre Atomes/volume * Flux de photons ionisants * Section transversale



$$\lambda = 912 \text{ \AA}$$
$$\rightarrow a_v = 6.2 \cdot 10^{-18} \text{ cm}^2$$
$$\rightarrow r_v = 2.83 \text{ \AA}$$

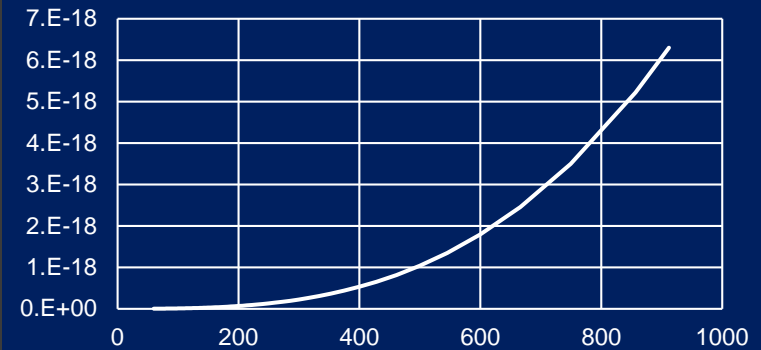
$$(r_H = 0.53 \text{ \AA})$$



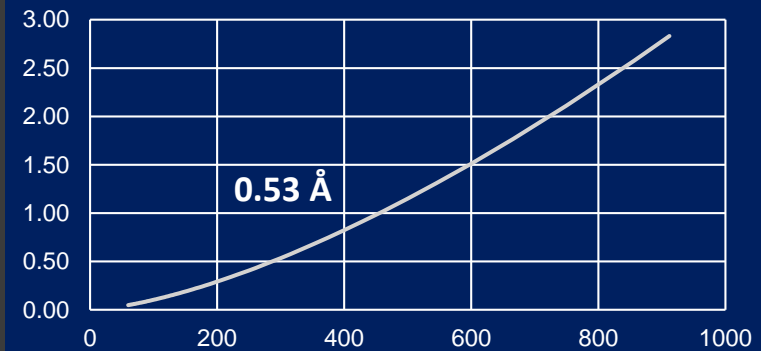
Section transversale
(Cross section)

$$a_\lambda = a_{\lambda_0} \cdot \left(\frac{\lambda}{\lambda_0}\right)^3$$

$a_v \text{ cm}^2$



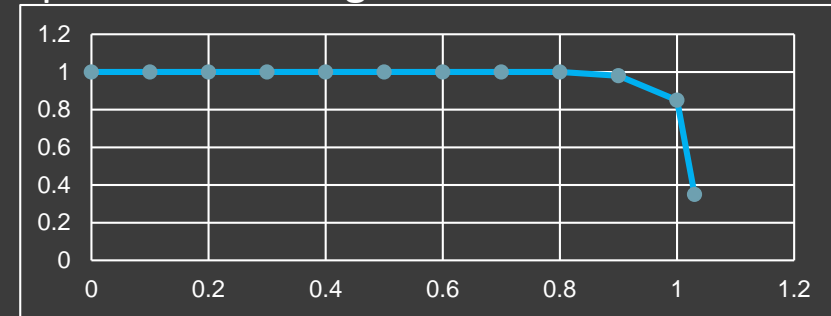
$r_v \text{ \AA}$



Longueur d'onde λ [\AA]

Modèles ionisation

Sphère de Strömgen



Radio survey of symbiotic stars

Seaquist, Taylor, Button 1984

$$X = \frac{4\pi a L}{\alpha} \left(\frac{m_H v}{M'} \right)^2$$

a = séparation

L = luminosité des photons ionisants

V = vitesse vent stellaire

M' = Perte de masse de la géante

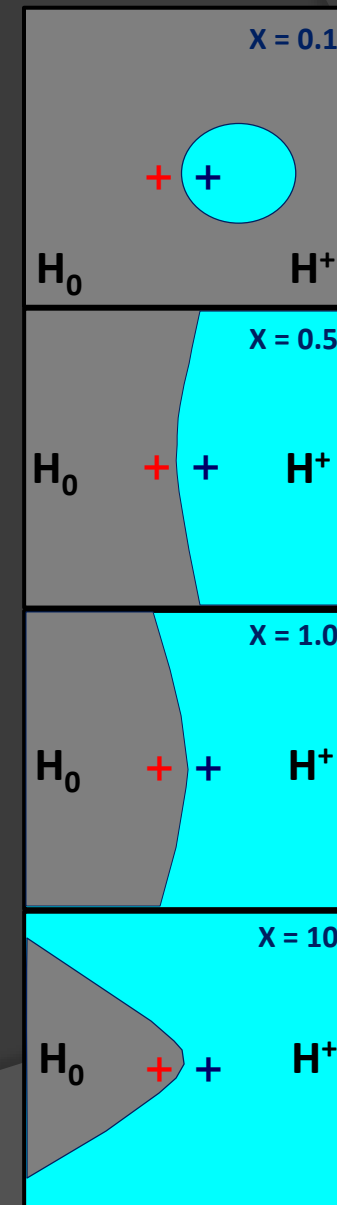
a = 3 AU

L = 10^{46} photons/seconde

V = 10 km.s^{-1}

M' = $10^{-7} M_{\odot}/\text{an}$

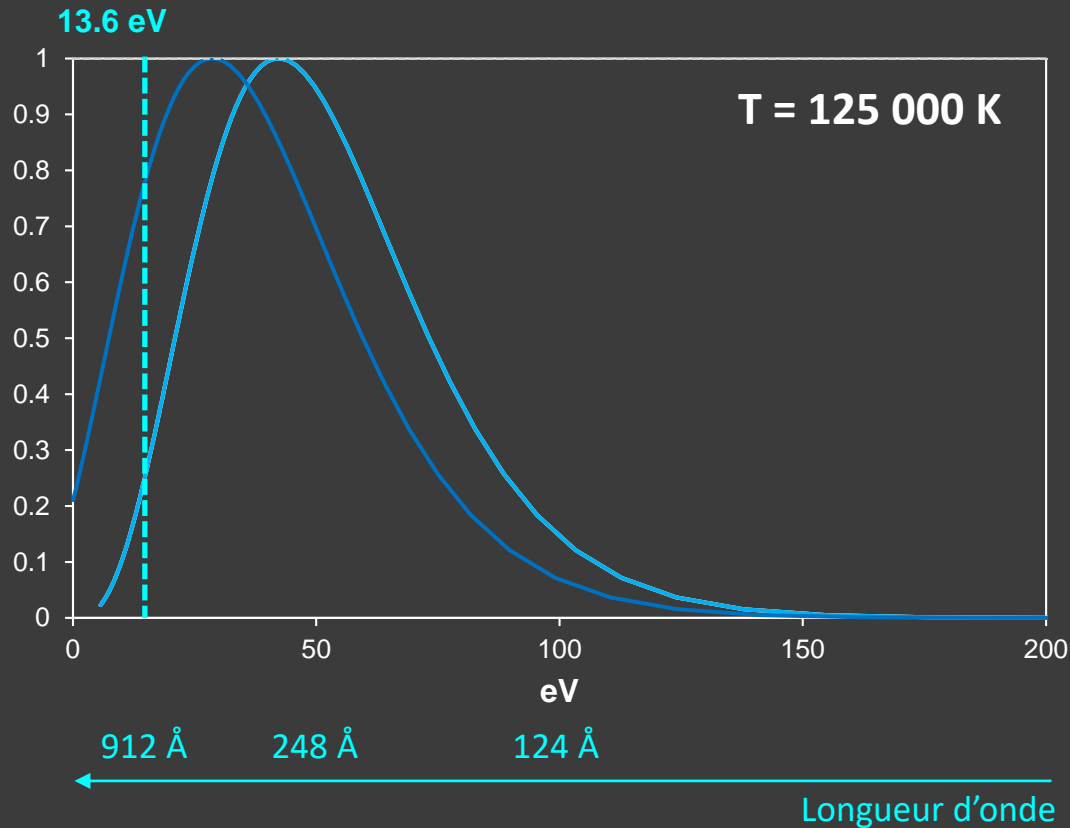
→ X = 1.5



Thermalisation des électrons

Distribution des électrons
après ionisation (exprimé en eV)

Distribution des photons
du rayonnement ionisant (exprimé en eV)



= une proportion importante des électrons libres possèdent une énergie suffisante pour ioniser H

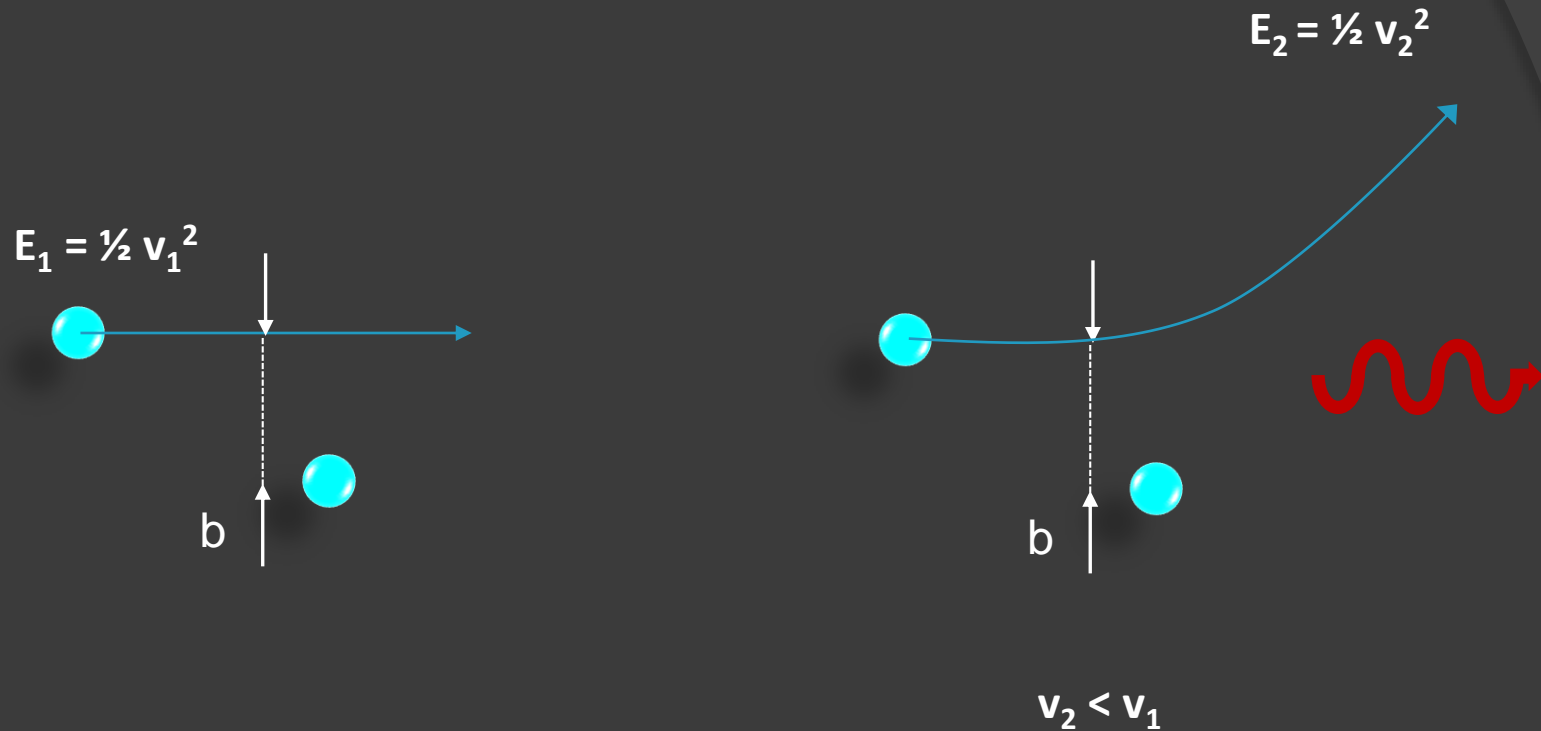
E(max) ~ 30 eV

V moyenne ~ 3000 km.s⁻¹

Thermalisation des électrons

Plasma créé par l'ionisation

Très forte interaction entre les électrons



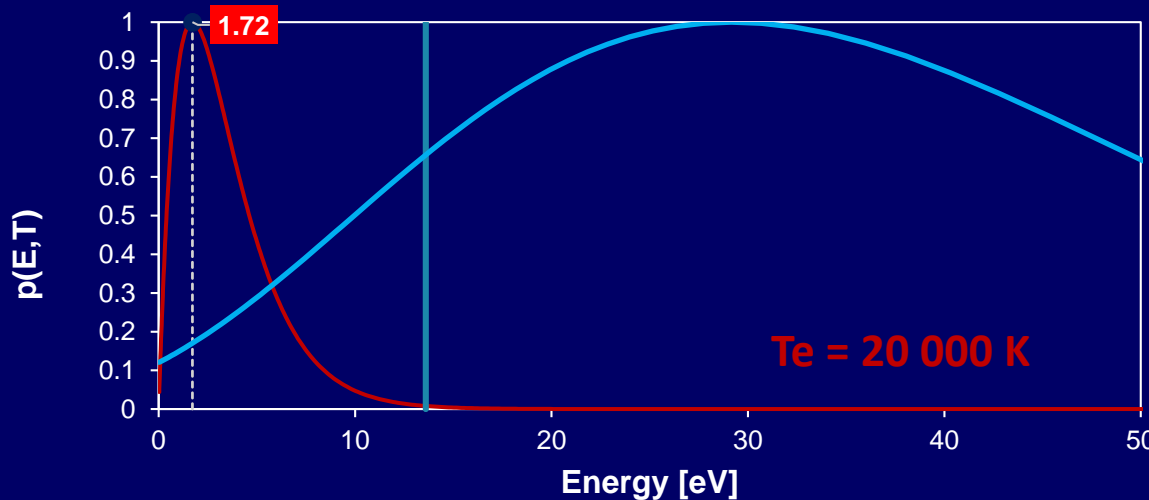
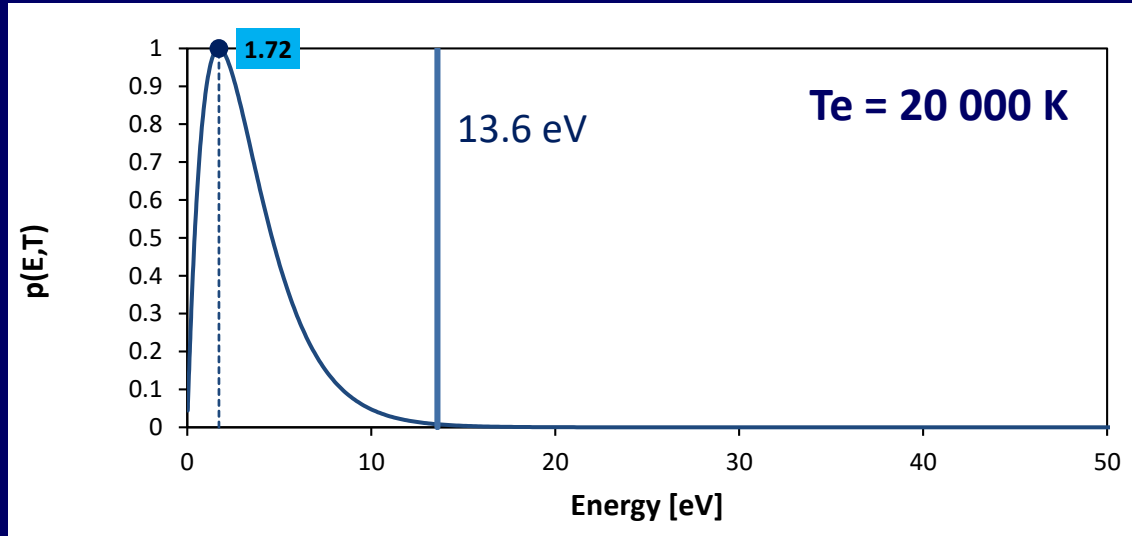
$$s = \pi b^2$$

$$s = 10^{-13} \text{ cm}^{-2}$$

Section efficace $\sim 10\,000$ x section efficace de l'ionisation
Thermalisation très rapide

Distribution de l'énergie des électrons après thermalisation

Distribution maxwellienne

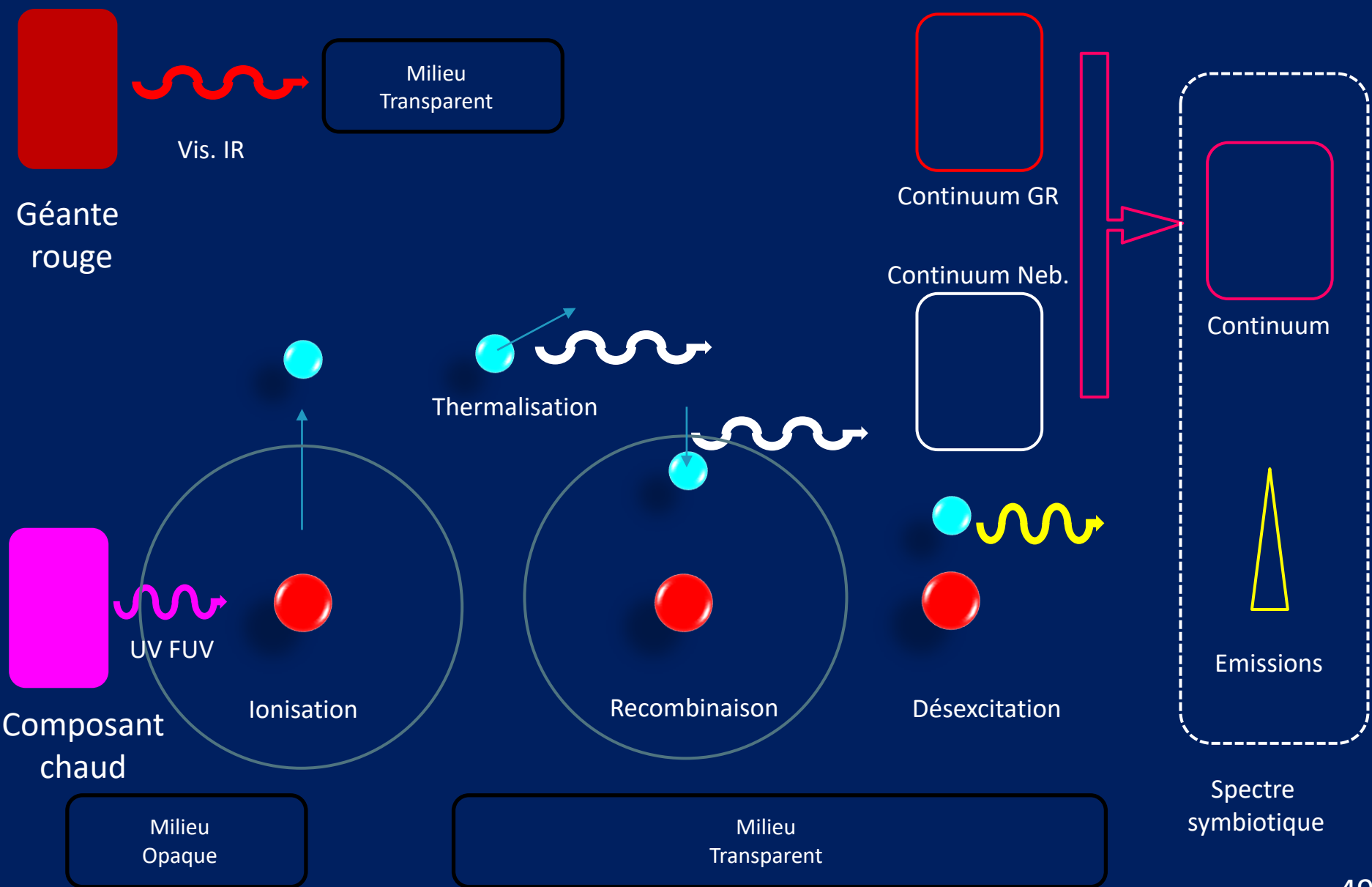


Après ionisation

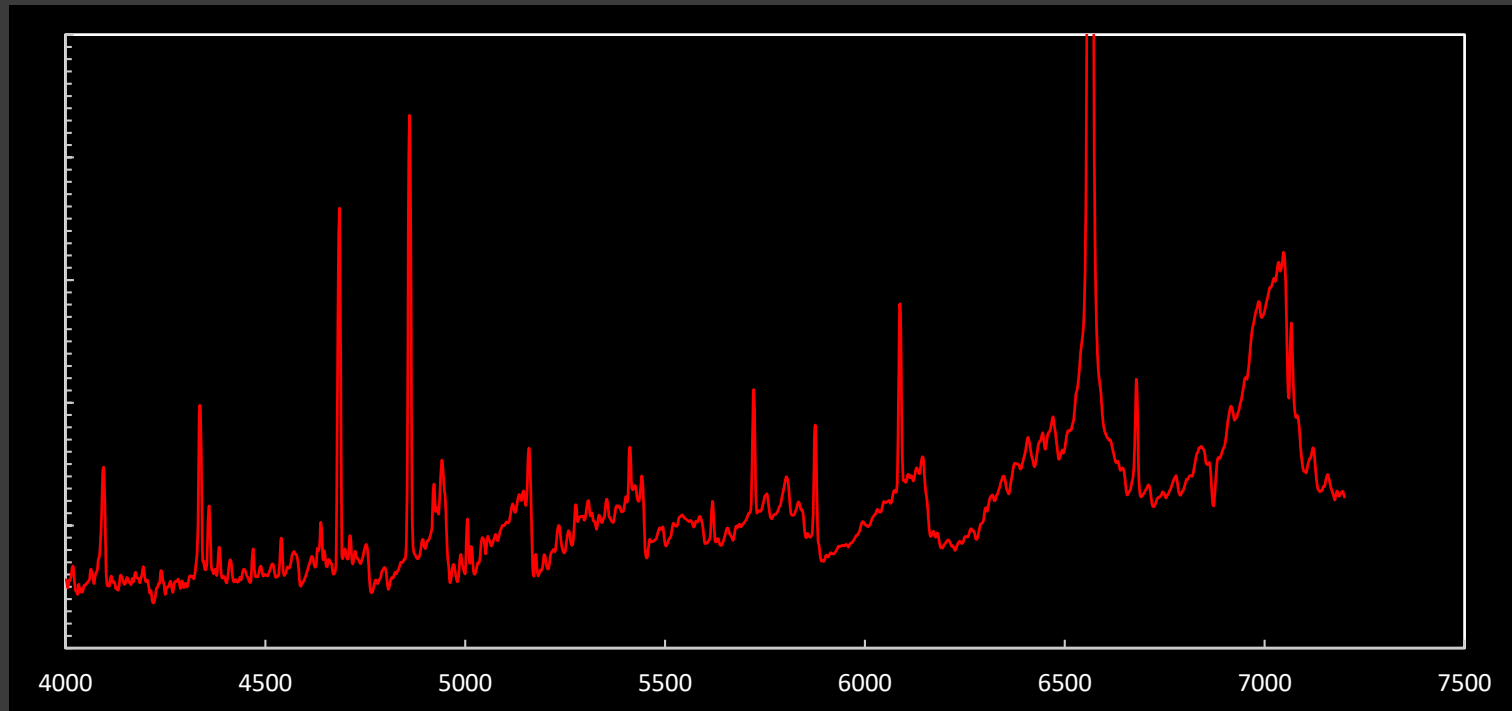
Après thermalisation

- 1 Énergie insuffisante pour ioniser H
- 2 Distribution d'énergie restituée au rayonnement lors de la recombinaison

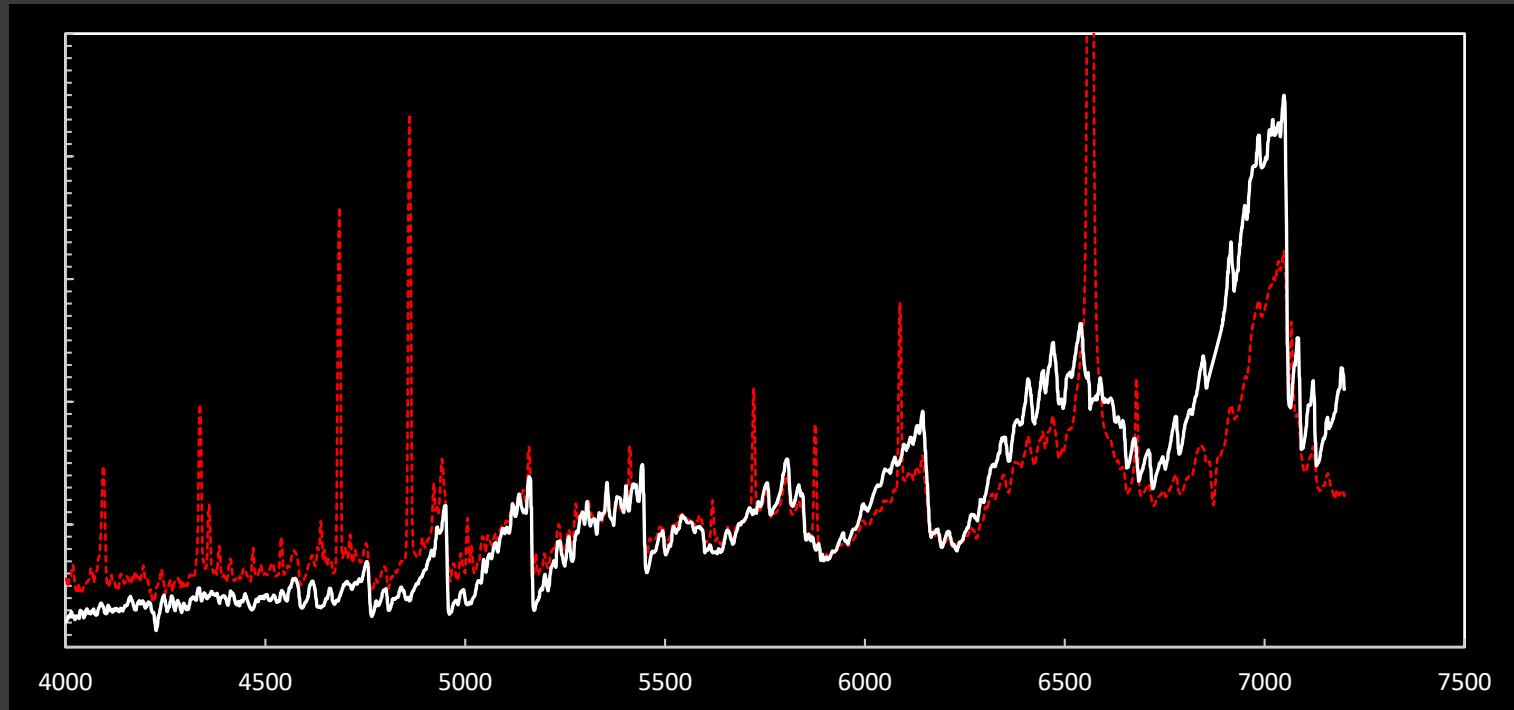
Formation du spectre symbiotique



CI Cygni 08-11-2015

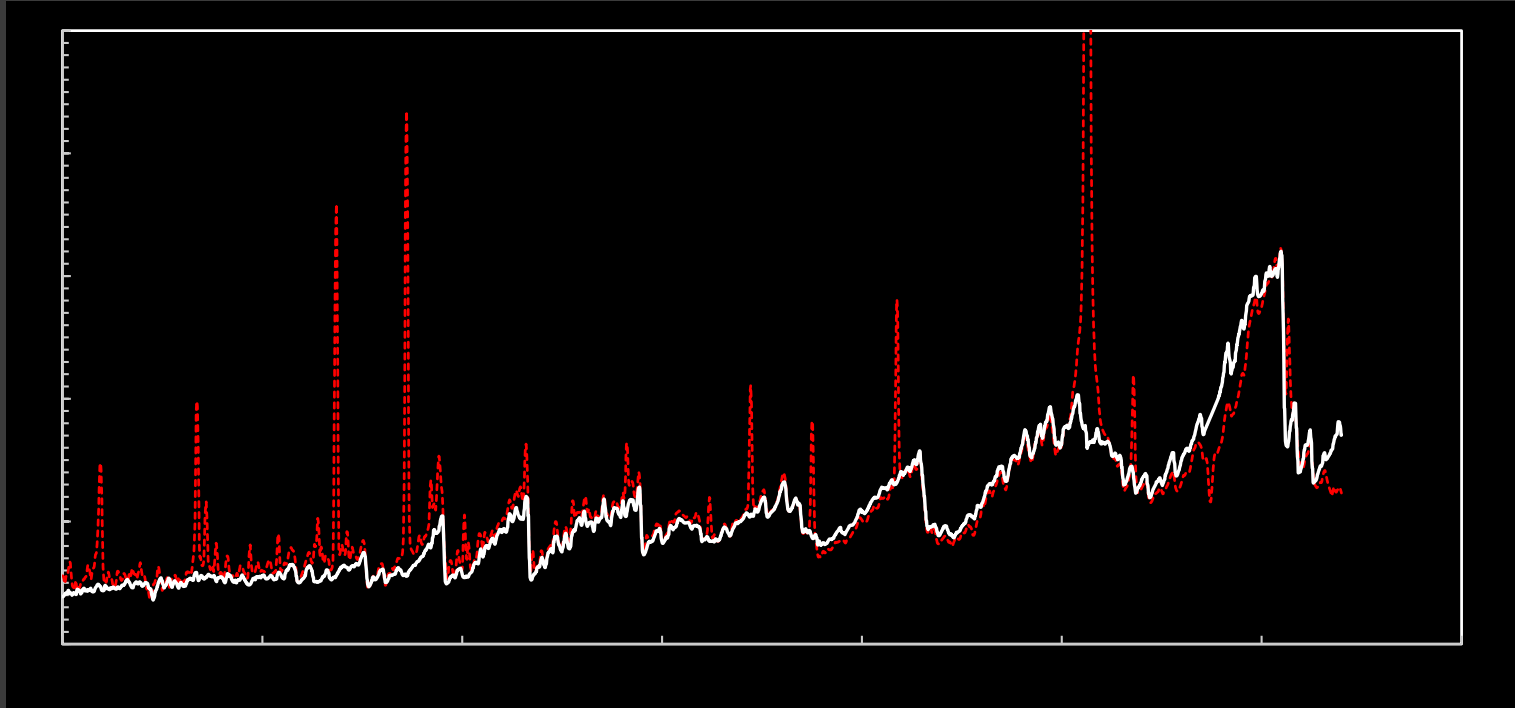


CI Cygni 08-11-2015



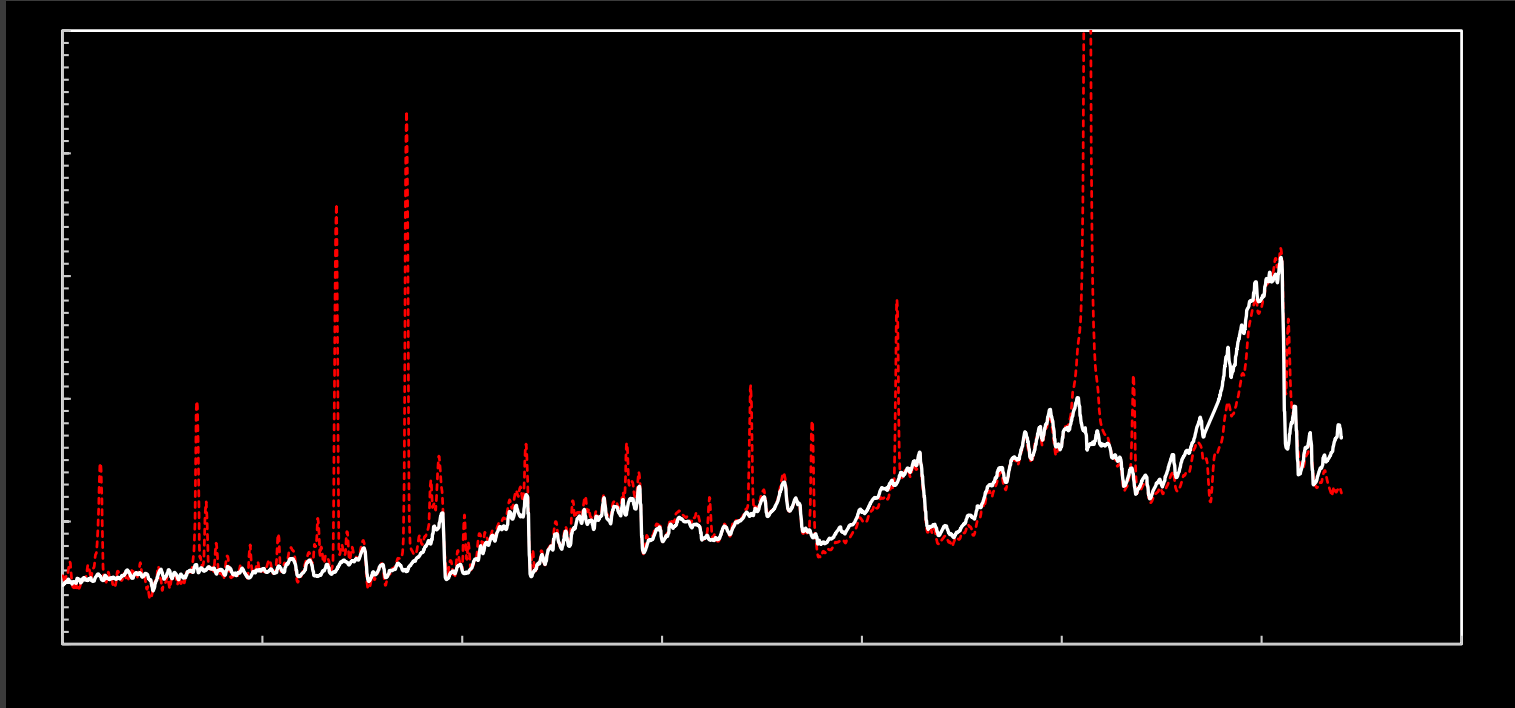
Comparaison avec spectre M5III (Fluckes)

CI Cygni 08-11-2015



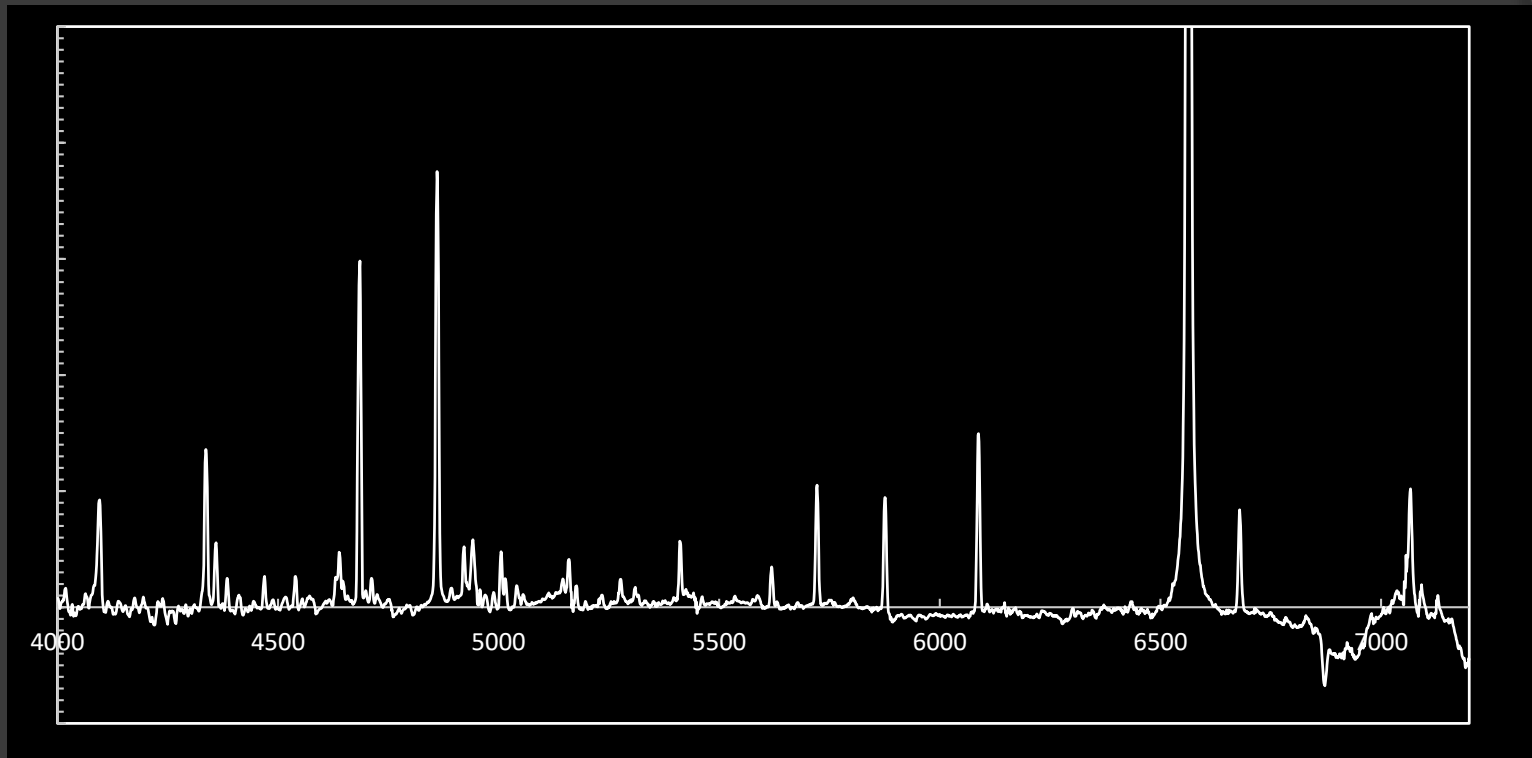
Spectre M5III (Fluckes) + Recombinaison H (15 000 K)

CI Cygni 08-11-2015



Spectre M5III (Fluckles) + Recombinaison H (15 000 K) + Hot Star (125 000 K)

CI Cygni 08-11-2015

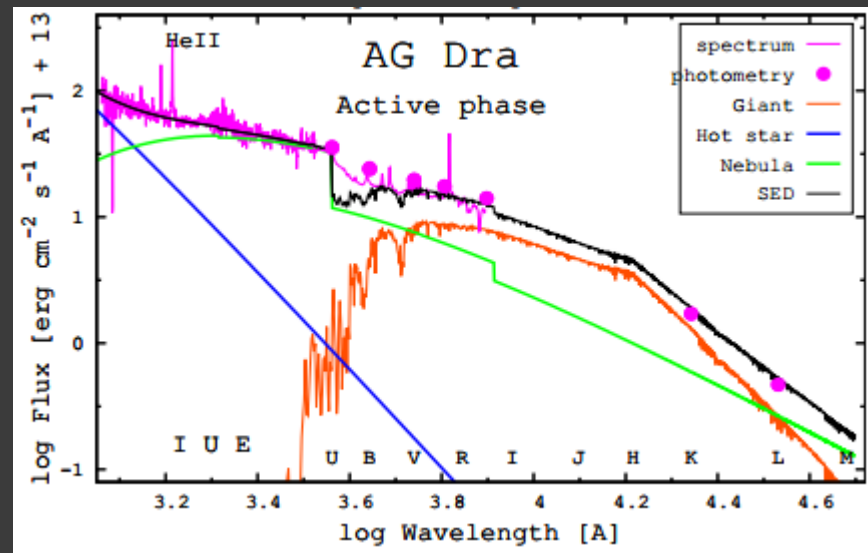


Soustraction du spectre composite (M5III+Continuum 15000 K + Hot Star 125000K)

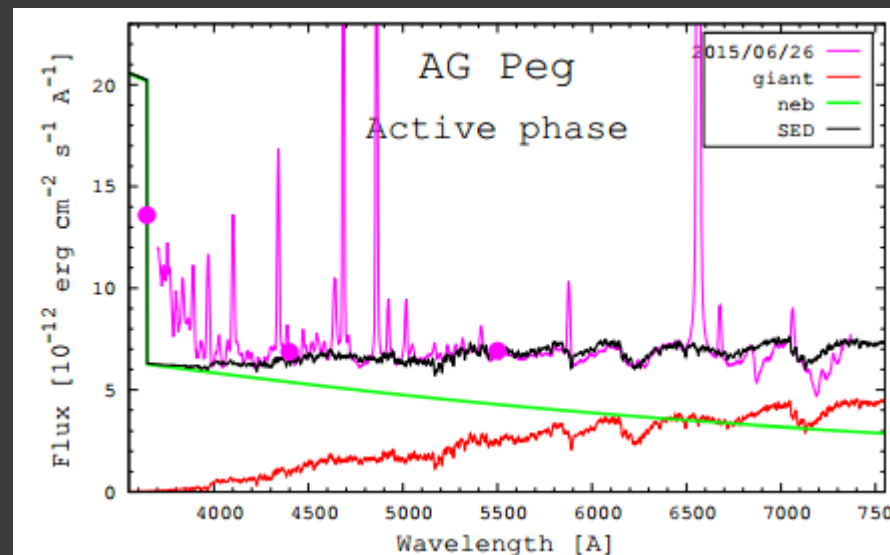
→ Mesure des raies (intensités)

Reconstitution du spectre composite

A. Skopal
in ARAS Eruptive Stars
Information Letter n°23
01-2016

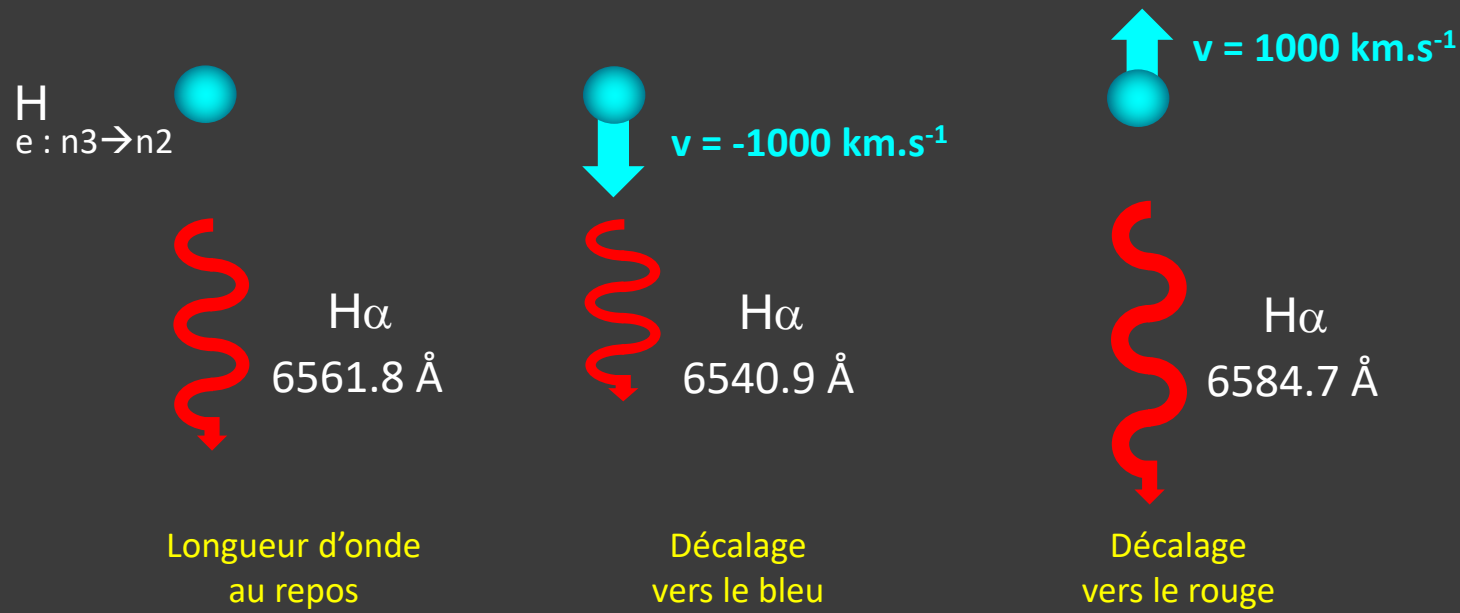


Spectre
Géante
Nébuleuse
Composant Chaud
Continuum composite



Spectre U. Sollecchia

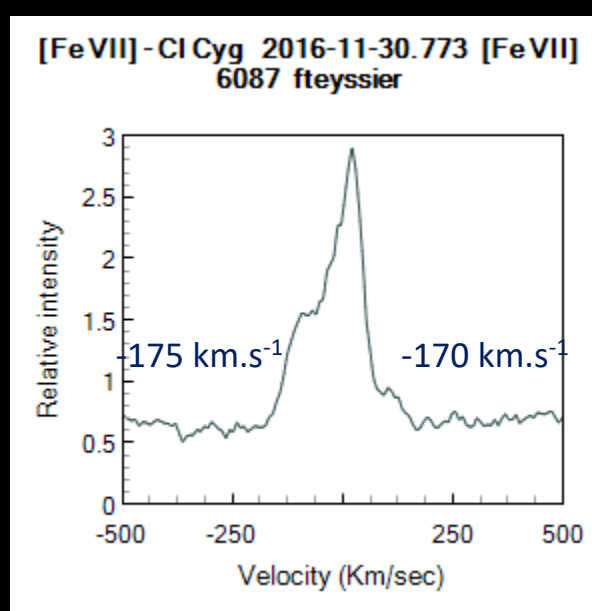
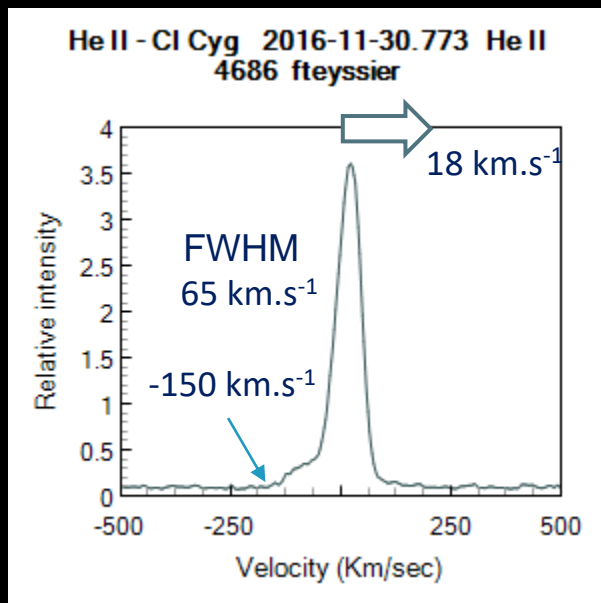
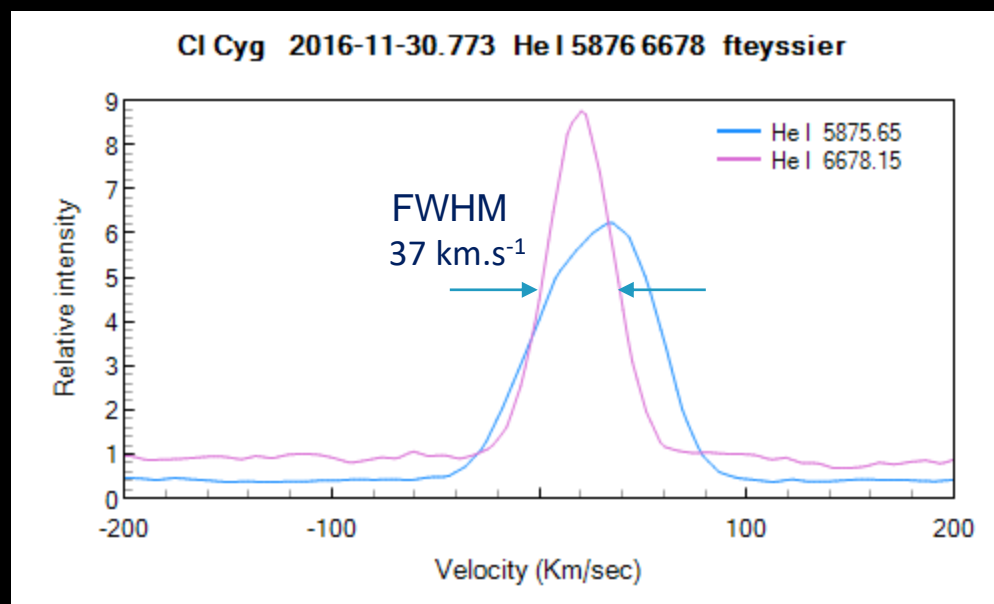
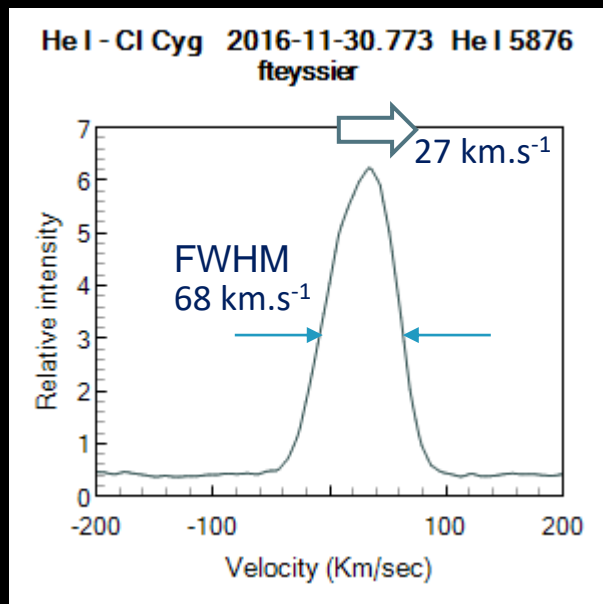
Effet doppler



La vitesse d'une électron émettant un photon
Modifie la longueur d'onde du photon

v (km.s ⁻¹)	λ (Å)
-2000	6519.1
-1000	6540.9
-500	6551.9
-200	6558.4
-100	6560.6
100	6565.0
200	6567.2
500	6573.8
1000	6584.7
2000	6606.6

Profil des raies

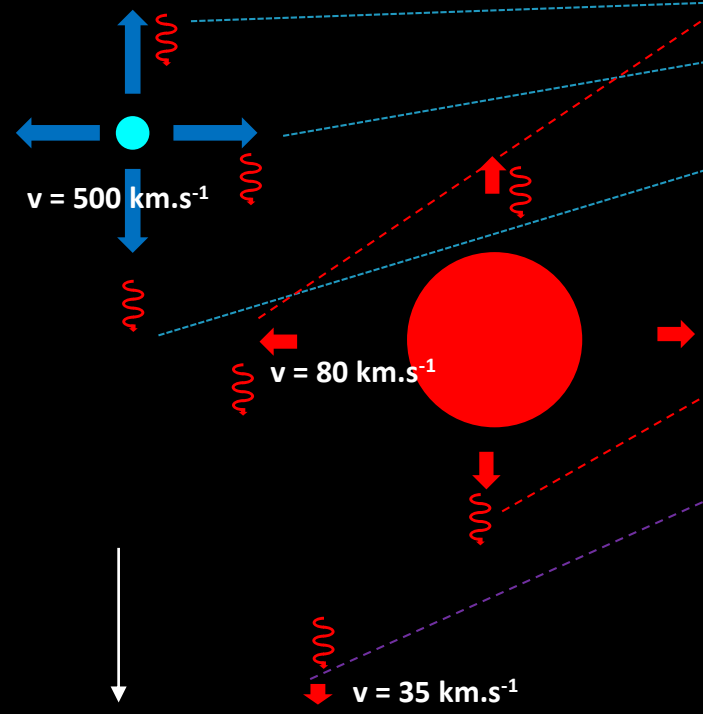
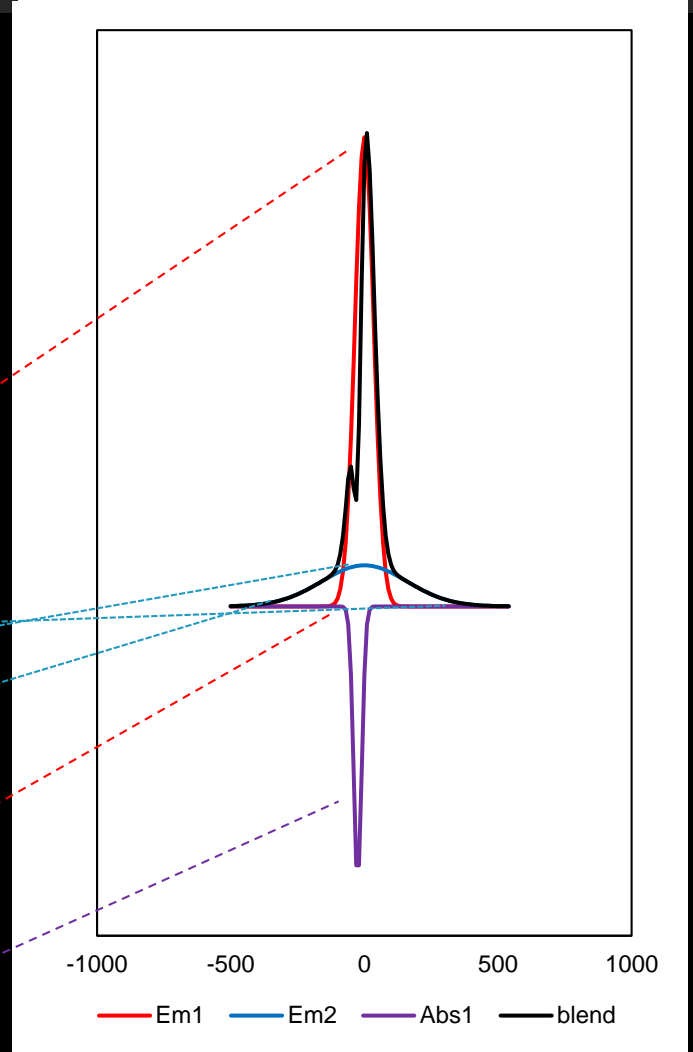
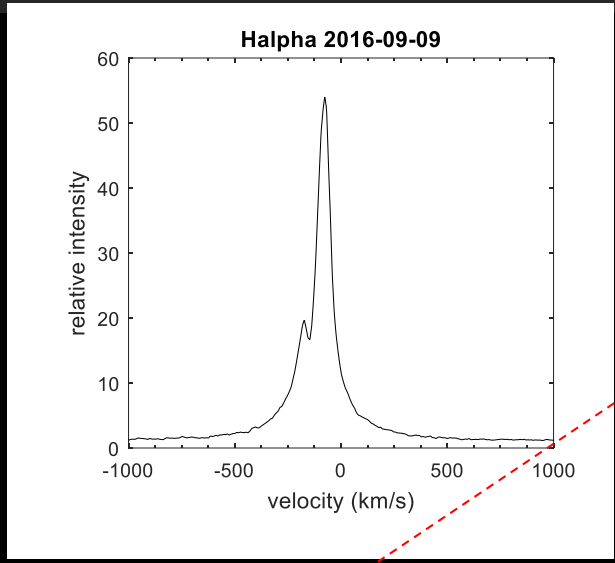


Conversion
Longueur d'onde
→ Vitesse radiale
Par rapport à la longueur d'onde
au repos

$$V_r = \Delta\lambda/\lambda * c$$

Profil des raies

Cl Cyg
Raie H α



- 1 Spectroscopie et Classification spectrale
- 2 La découverte des Etoiles Symbiotiques
- 3 Modèle d'une Etoile Symbiotique
- 4 Formation du spectre
- 5 Les Symbiotiques à l'état calme
- 6 Le Zoo des Symbiotiques
- 7 Les Symbiotiques en Outburst
- 8 Contribution des amateurs

Variations orbitales

**Modèle
EG And**

$P_{orb} = 482.6 \text{ d}$
 $e \sim 0$

$d = 1-5 \text{ U.A.}$

Vent Stellaire
 $M' = 10^{-7} - 10^{-8} M_{\odot}/\text{an}$

Nébuleuse

$T_e = 15\,000 \text{ K}$
Matière solaire
 $N = 10^8 \text{ cm}^{-3}$
 $M = 10^{-6} M_{\odot}$

Géante Rouge

M2.4 III
3700 K
 $R = 75 R_{\odot}$
 $M = 1.5 (0.6) M_{\odot}$
 $L = 950 L_{\odot}$

Naine Blanche

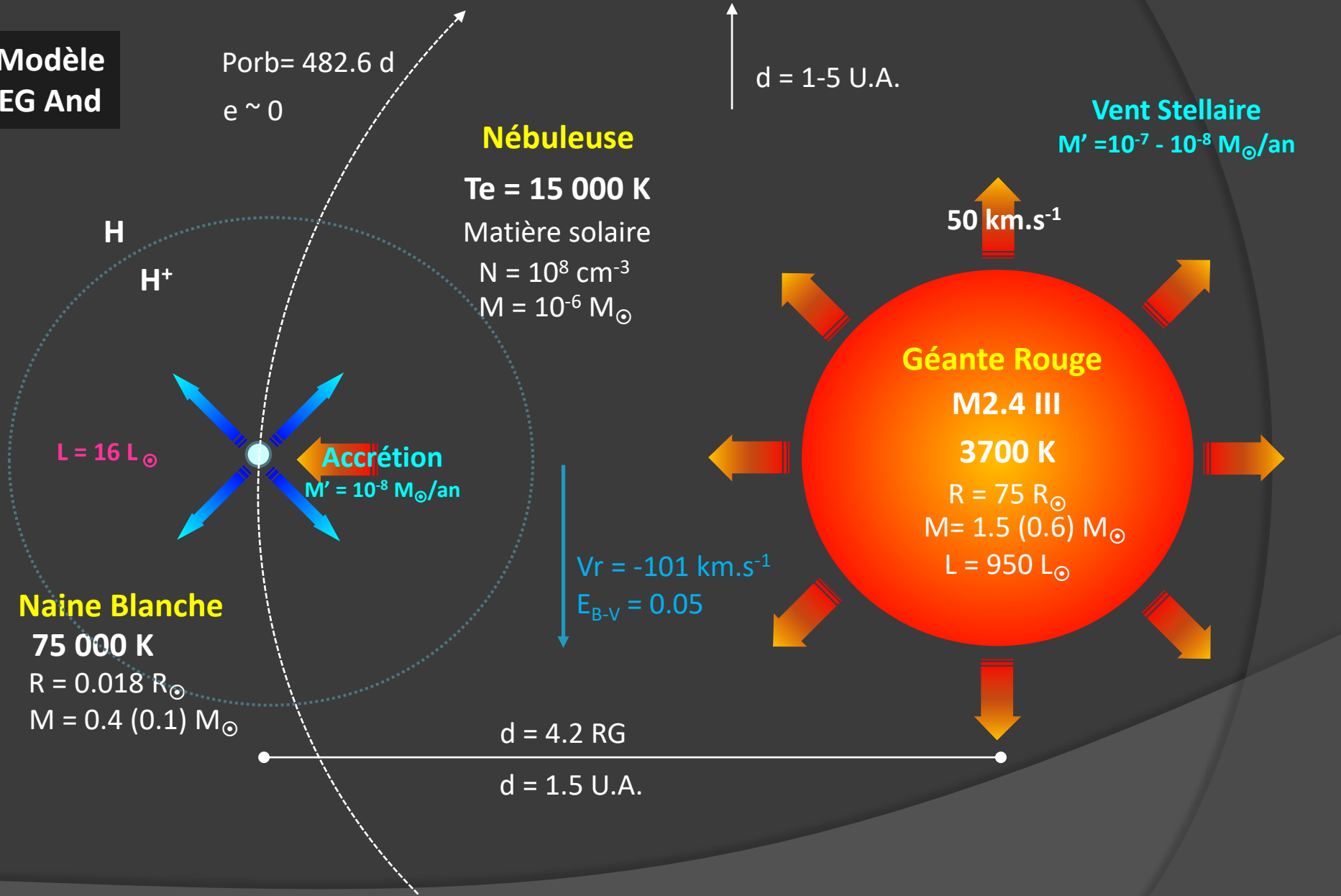
75 000 K
 $R = 0.018 R_{\odot}$
 $M = 0.4 (0.1) M_{\odot}$

Accrétion
 $M' = 10^{-8} M_{\odot}/\text{an}$

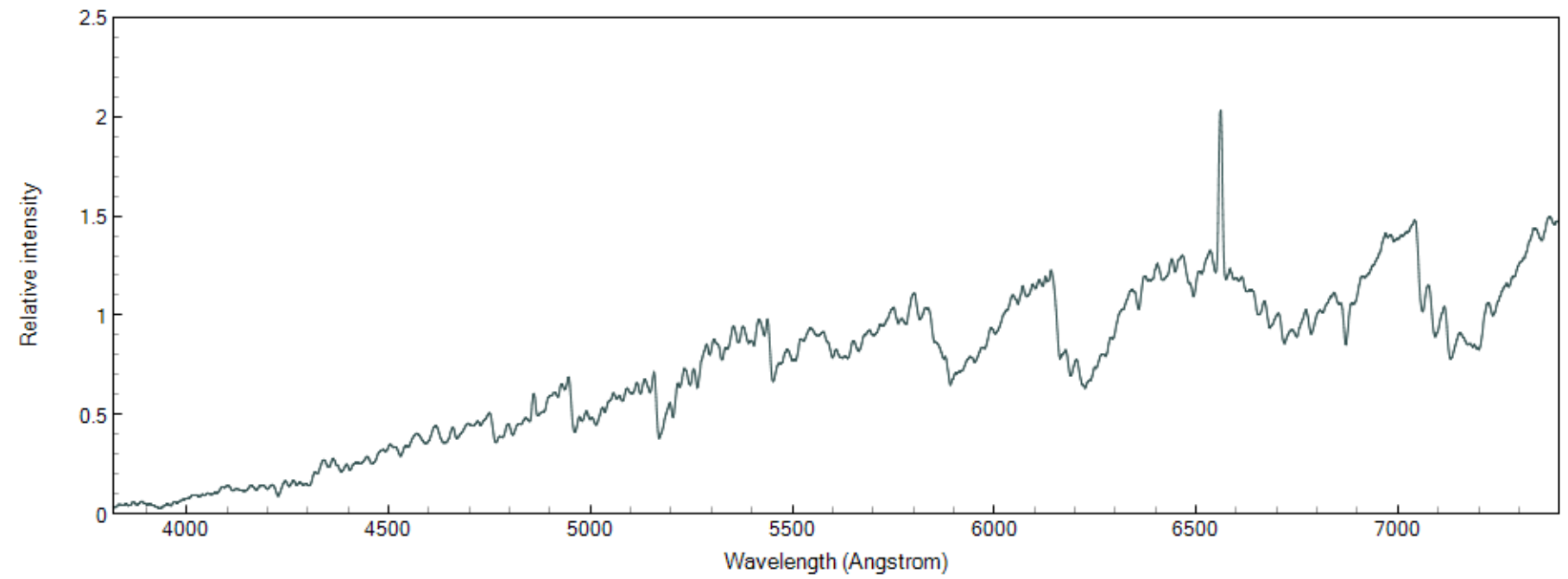
$V_r = -101 \text{ km.s}^{-1}$
 $E_{B-V} = 0.05$

$d = 4.2 \text{ RG}$

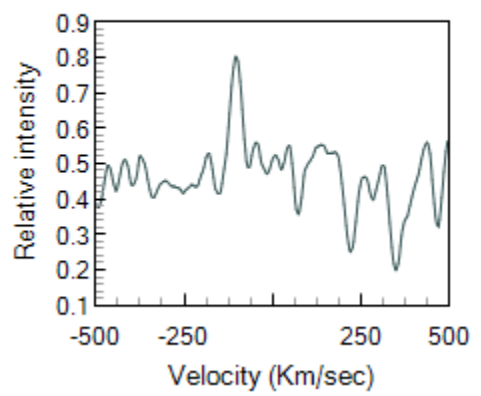
$d = 1.5 \text{ U.A.}$



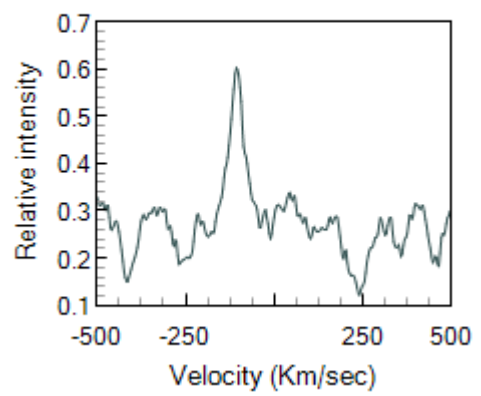
EG And 2016-10-22.958 Jacques Montier



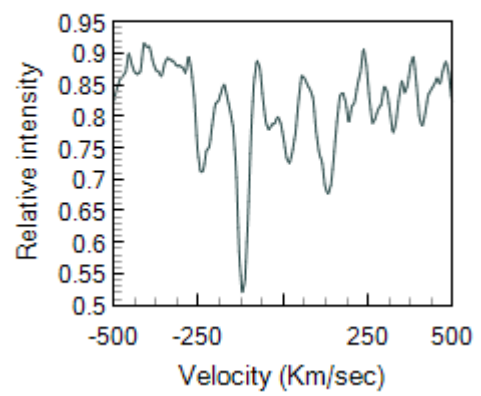
[OIII]-EGAnd 2016-10-30.813 fteyssier



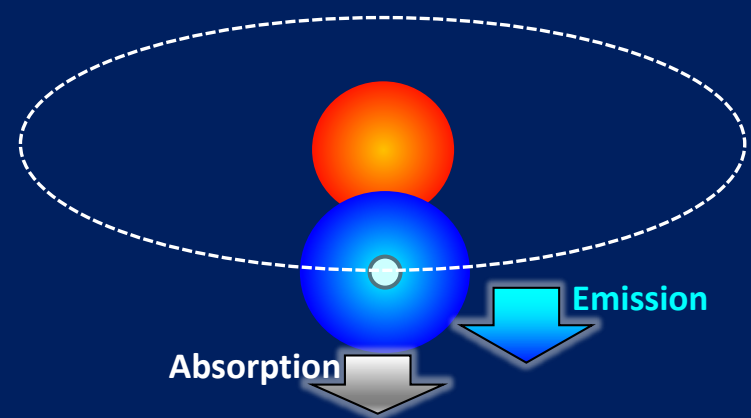
[OIII]-EGAnd 2016-10-30.813 fteyssier



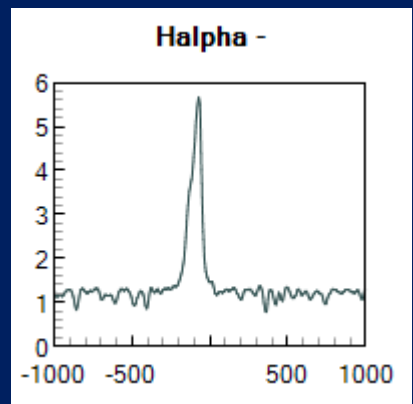
HeI-EGAnd 2016-10-30.813 fteyssier



Série temporelle
H α

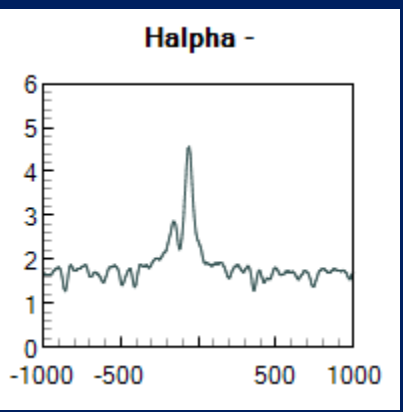


Phase = 0.99

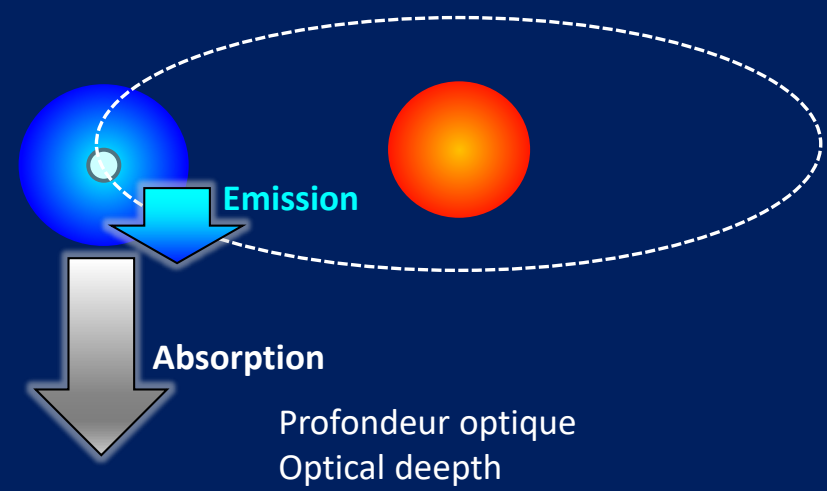


Série temporelle
H α

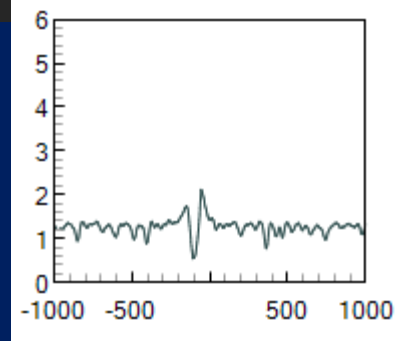
Phase = 0.24



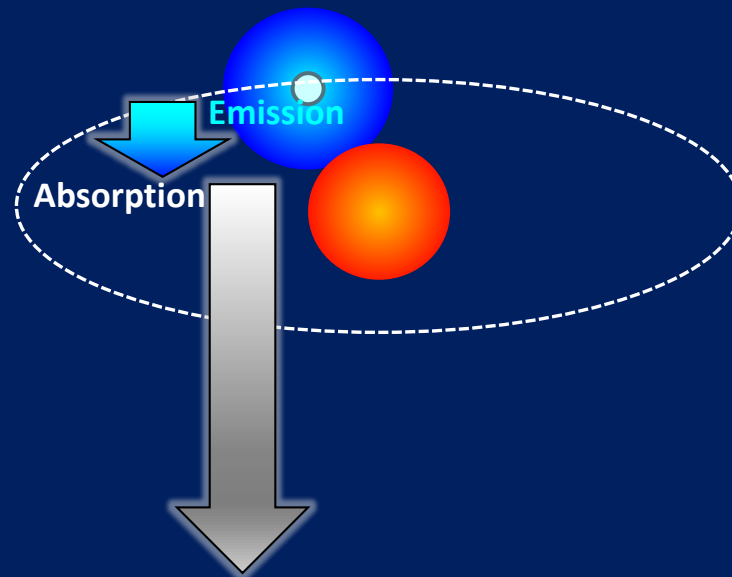
01-11-2015



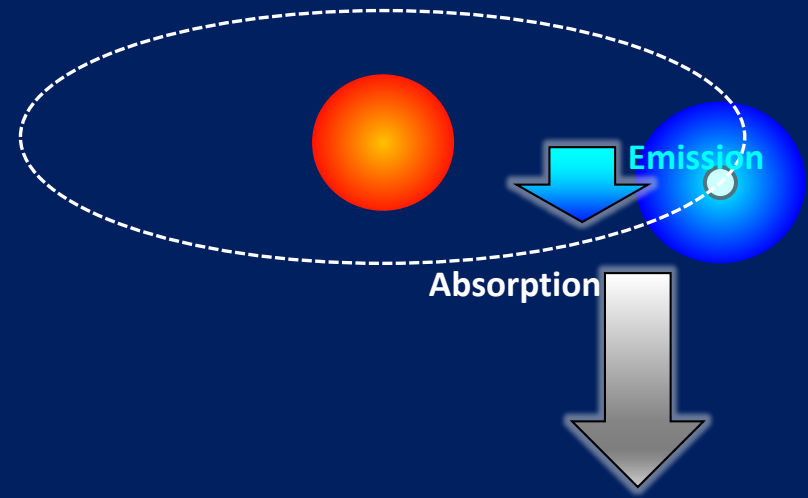
Série temporelle
H α



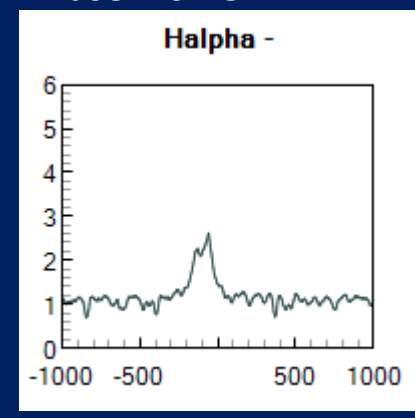
Phase = 0.45



Série temporelle
H α

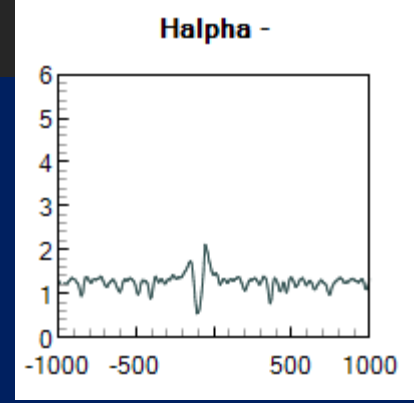


Phase = 0.78



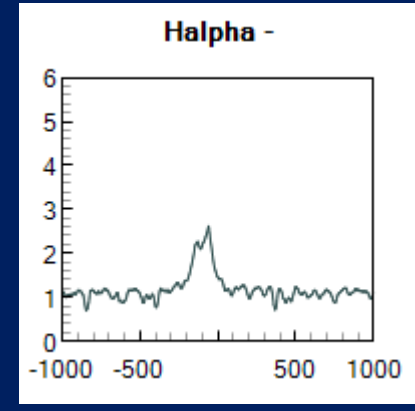
22-07-2016

Série temporelle
H α



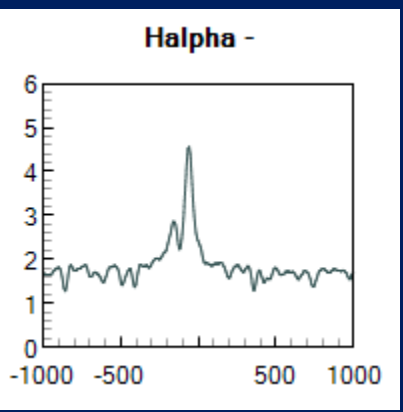
Phase = 0.45

Phase = 0.78

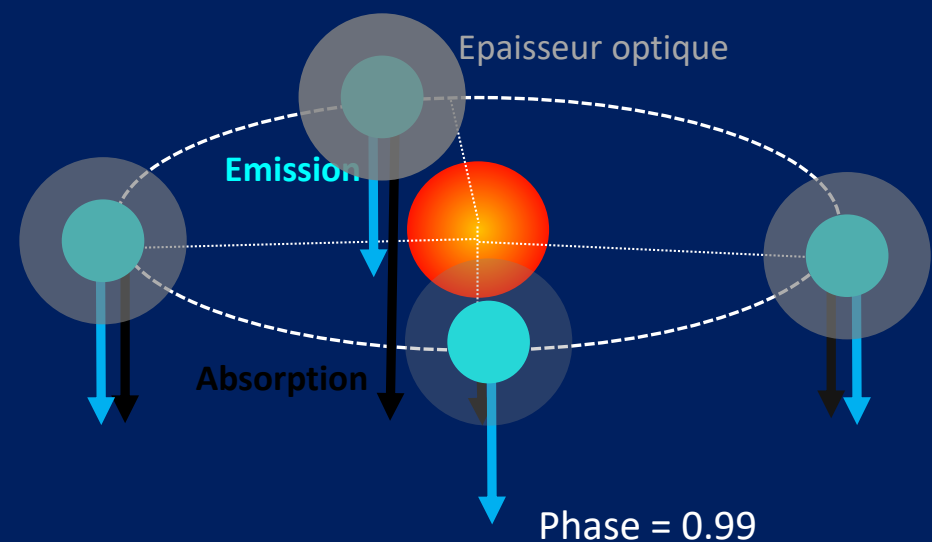


22-07-2016

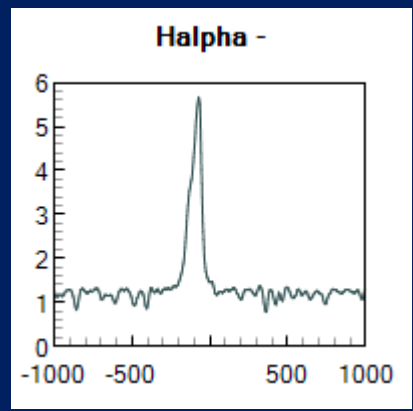
Phase = 0.24



01-11-2015

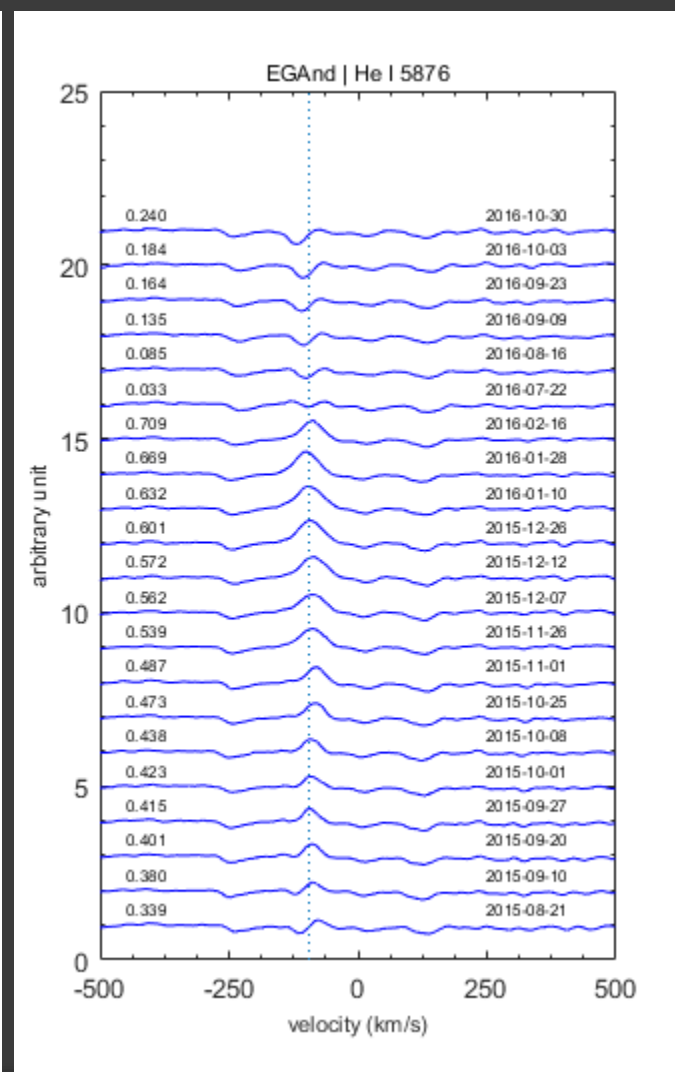
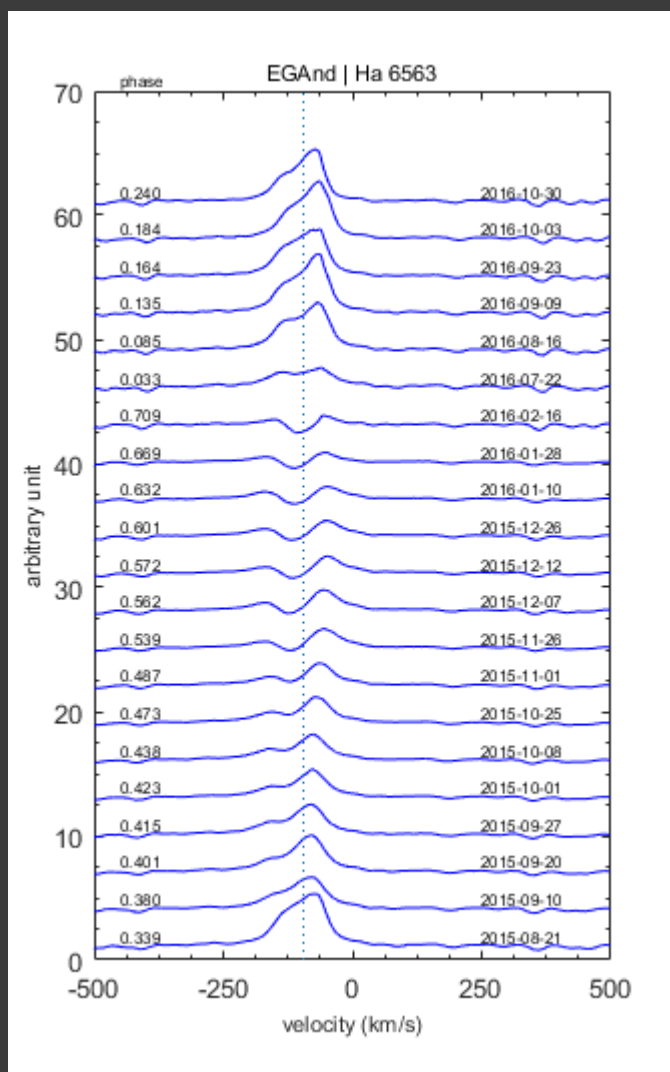


Note Profile $\phi(0.78) \neq \phi(0.24)$



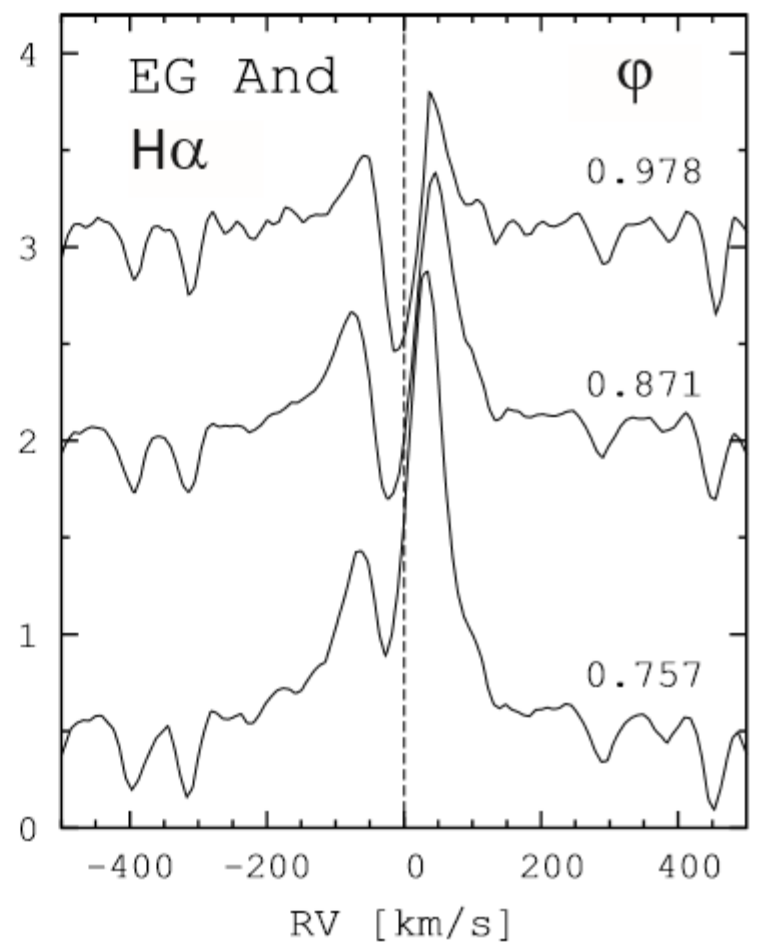
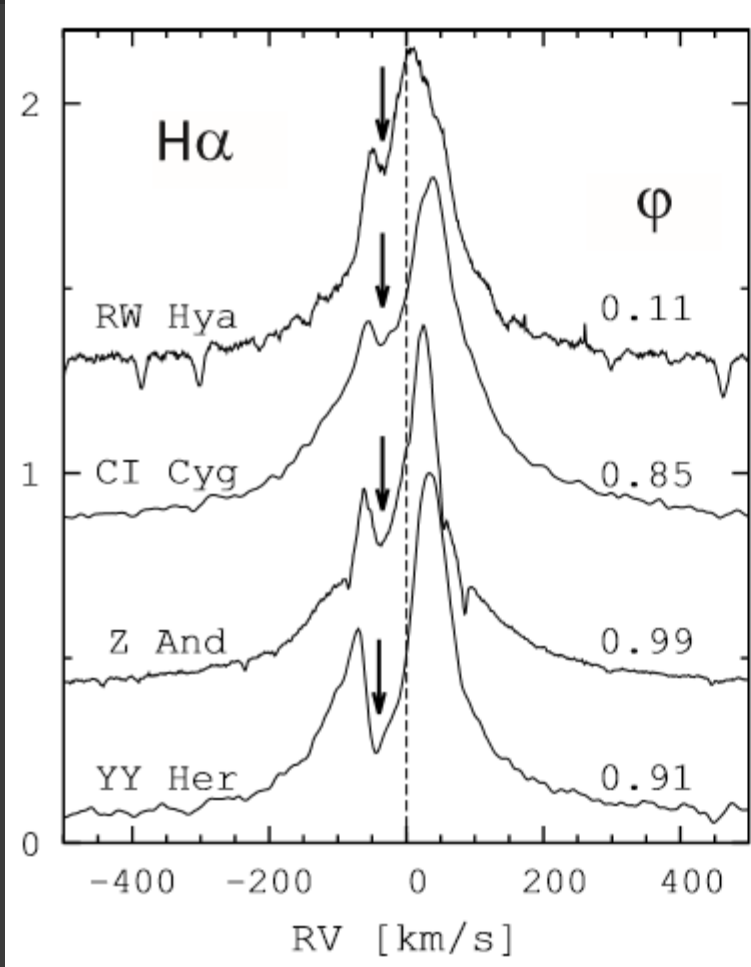
30-10-2016

21-08-2015 au 30-10-2016



Note Anticorrélation

Série temporelle H α



H-alpha line profiles
Iverson et al. (1994, A&AS, 103, 201).

Spectres F. Teyssier
Analyse : A. Skopal

He

Etat fondamental
Spins opposés



1^{ère} ionisation



I.P. = 24.6 eV



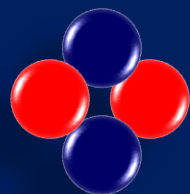
2^{ème} ionisation



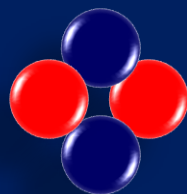
I.P. = 54.4 eV



He

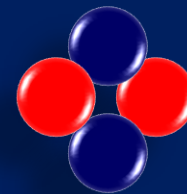


He⁺



He I

He⁺⁺



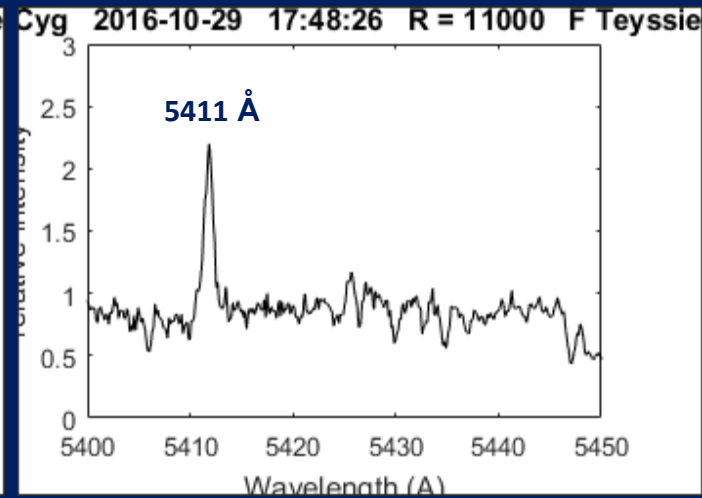
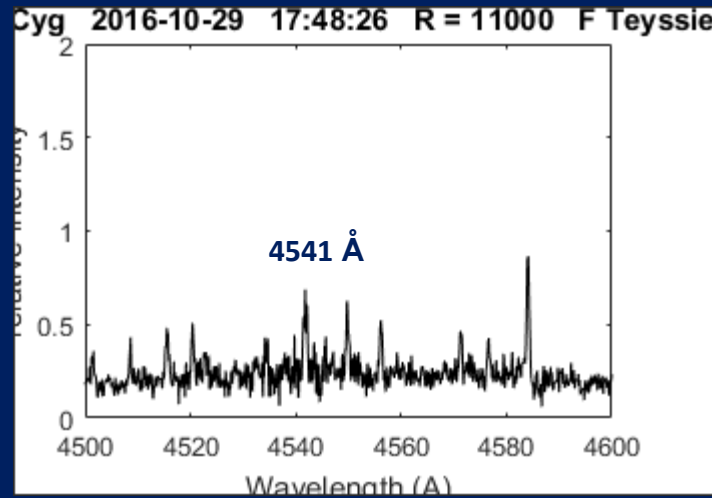
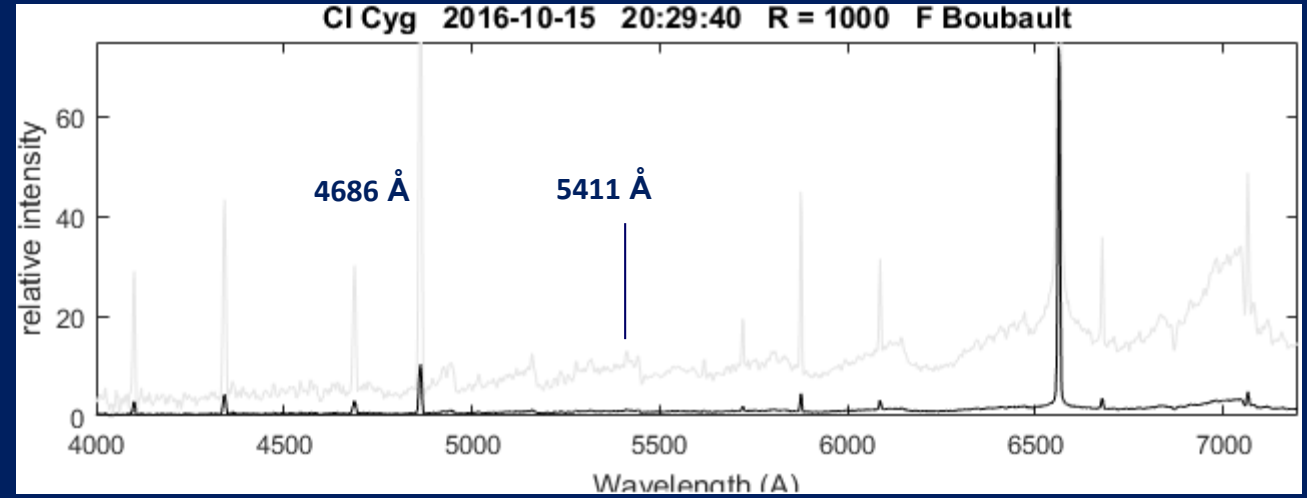
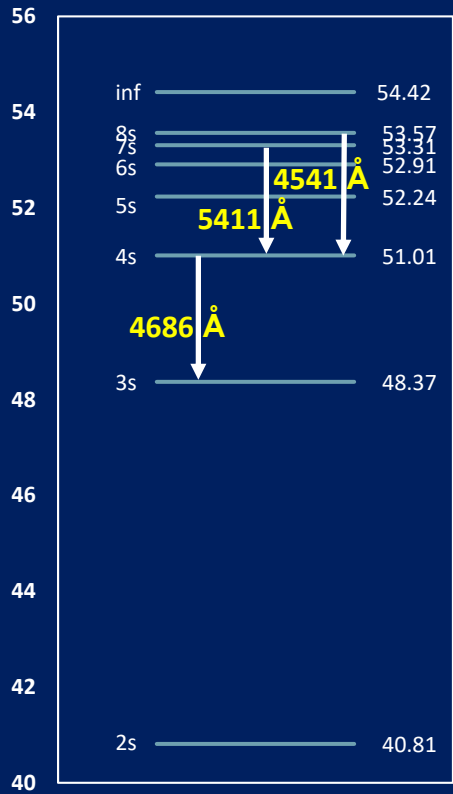
He II

$$\lambda = 12403 / \text{IP}$$

$$\lambda = 500 \text{ \AA}$$

$$\lambda = 225 \text{ \AA}$$

Recombinaison



Evaluation de la température Du composant chaud T*

$$T_4 = 19.38 K^{1/2} + 5.13$$

$$K = 2.22 F(\text{He II } 4686) / [4.16 F(\text{H}\beta) + 9.94 F(\text{He I } 4471)]$$

$$T_4 = T / 10\,000$$

$$K \sim 0.53 F(\text{He II } 4686) / F(\text{H}\beta)$$

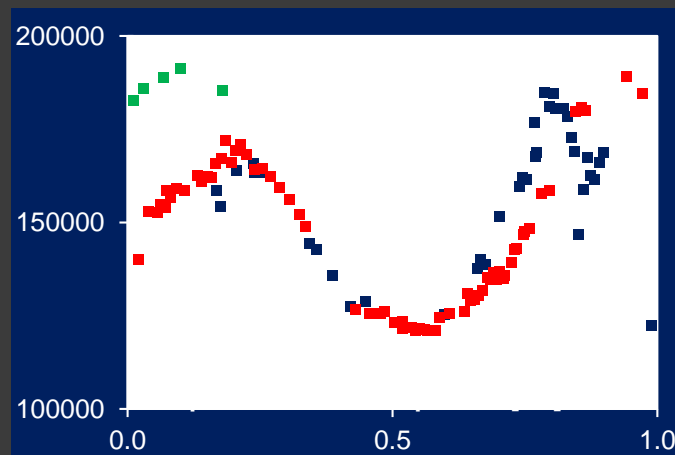
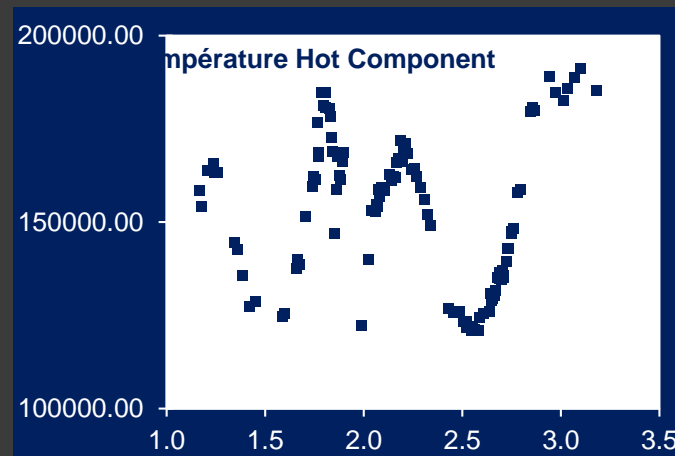
Spectres R = 1000

F. Teyssier

D. Boyd

J. Guarro

CI Cygni 2011-03-19 _ 2015-11-30



Phase orbitale

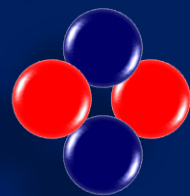
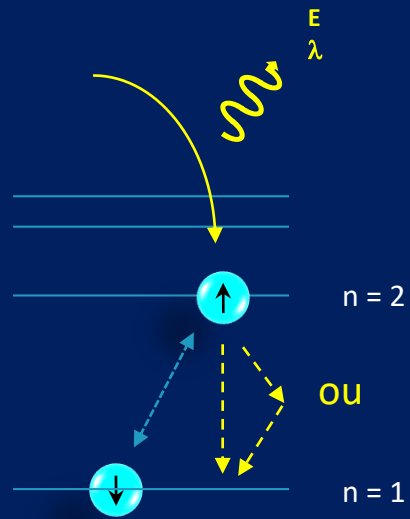
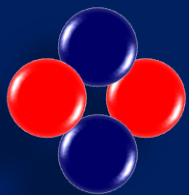
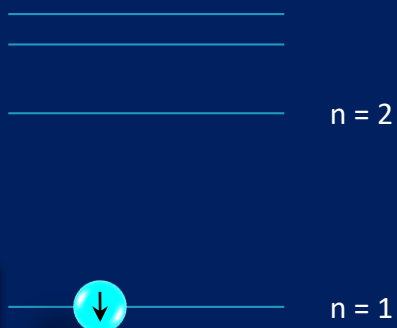
P = 853.8 jours

[Fekel & al., 2000]

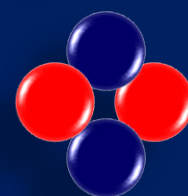
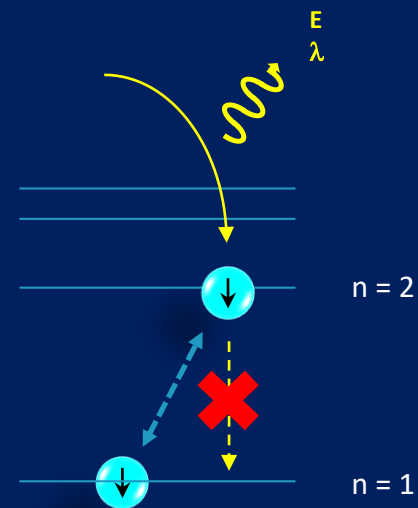
Helium

He I

Recombinaison



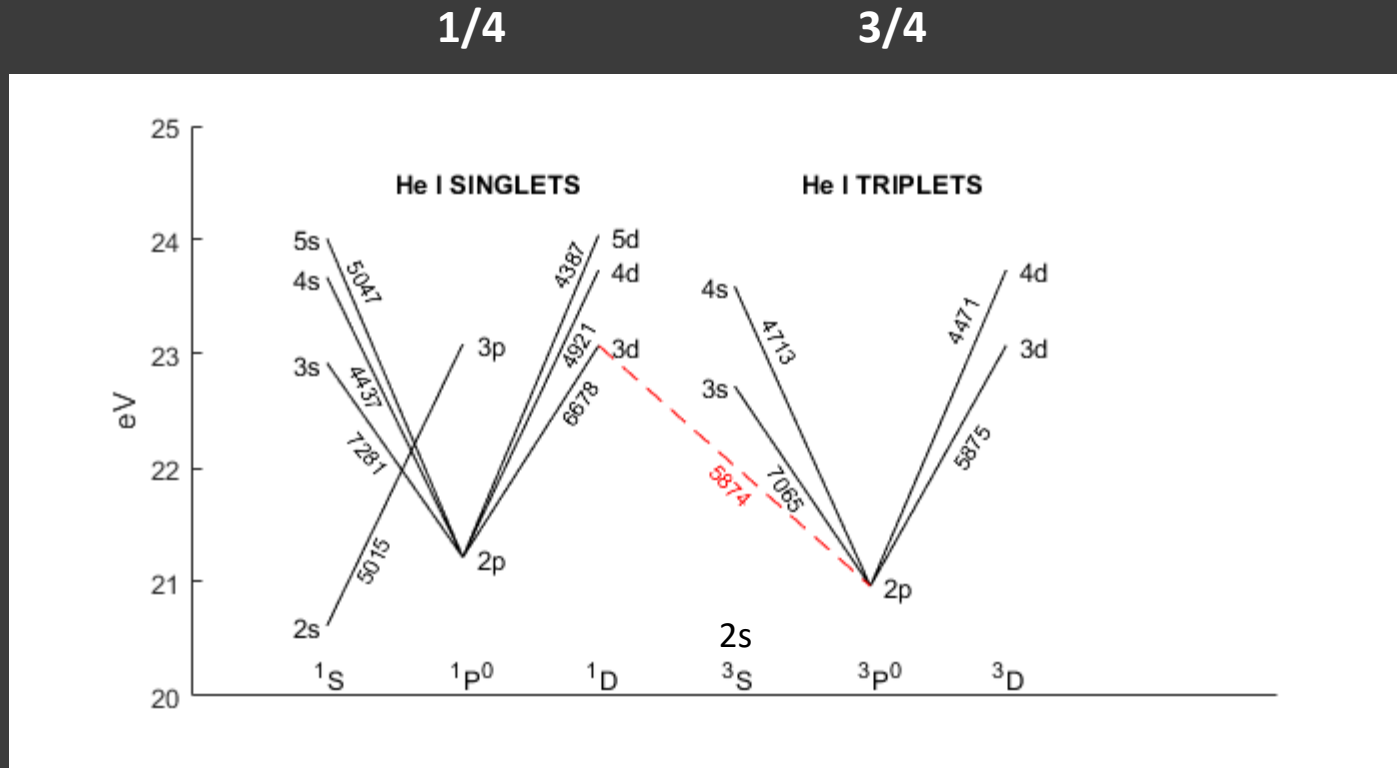
Singlet
(*singlet*)



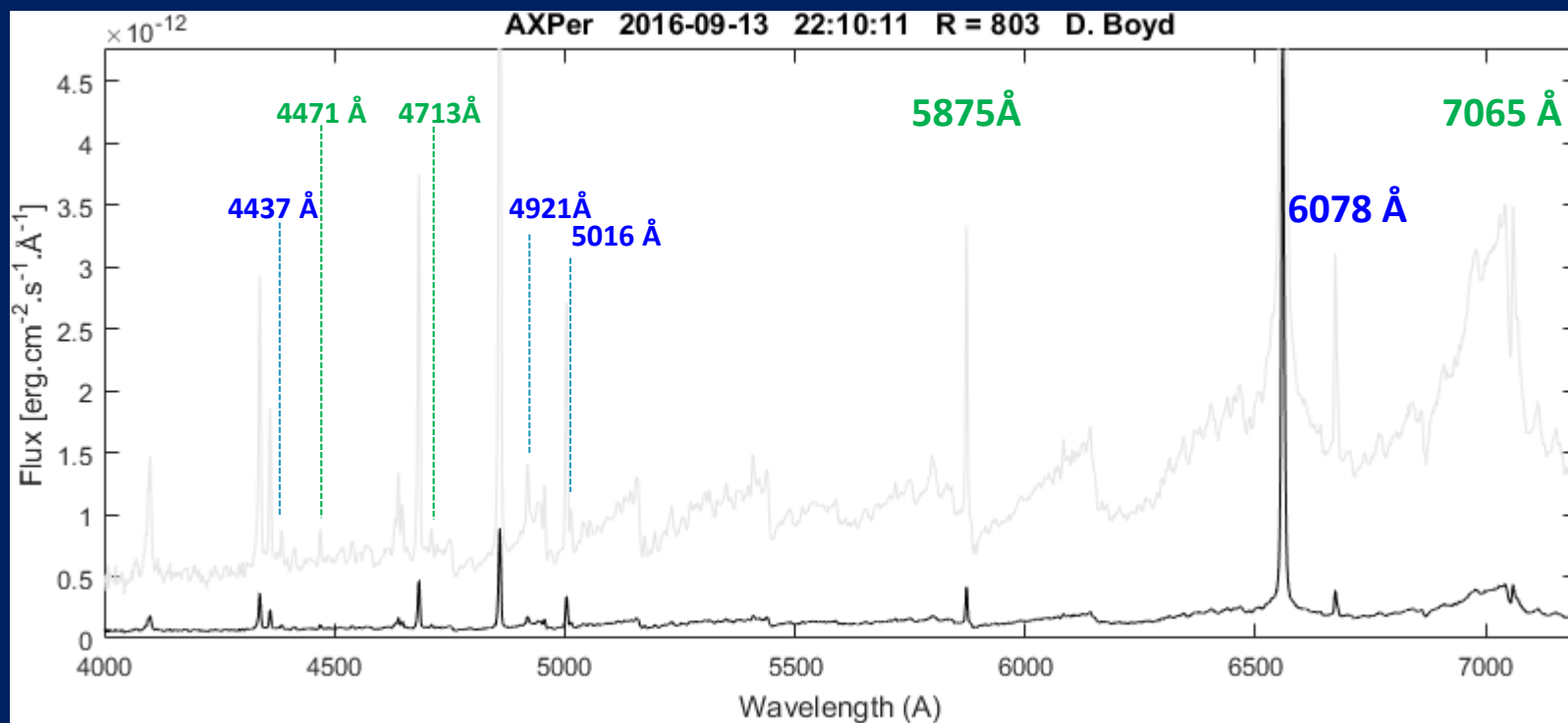
Triplet
(*singlet*)

Diagramme de Grotrian HeI singlets et triplets

Principales raies He I dans le domaine visible



Hélium He I



Singlets



Transition	λ (Å)
4s \rightarrow 2p	4437
4d \rightarrow 2p	4921
3p \rightarrow 2s	5015
3d \rightarrow 2p	6678

Triples



Transition	λ (Å)
4d \rightarrow 2p	4471
4s \rightarrow 2p	4713
3d \rightarrow 2p	5875
3s \rightarrow 2p	7065

Hélium He I

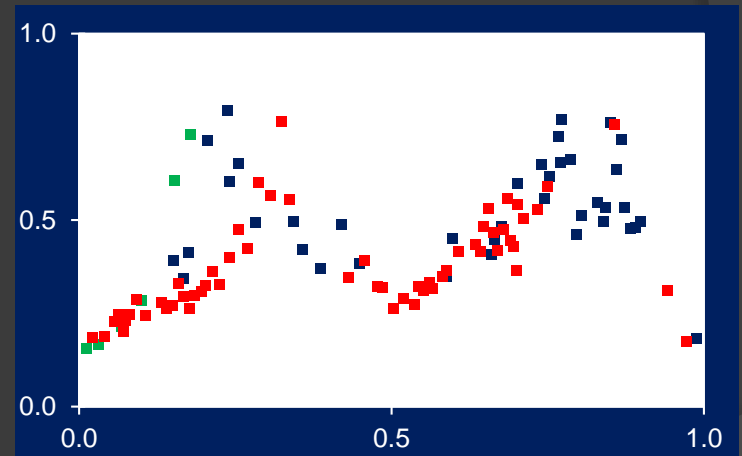
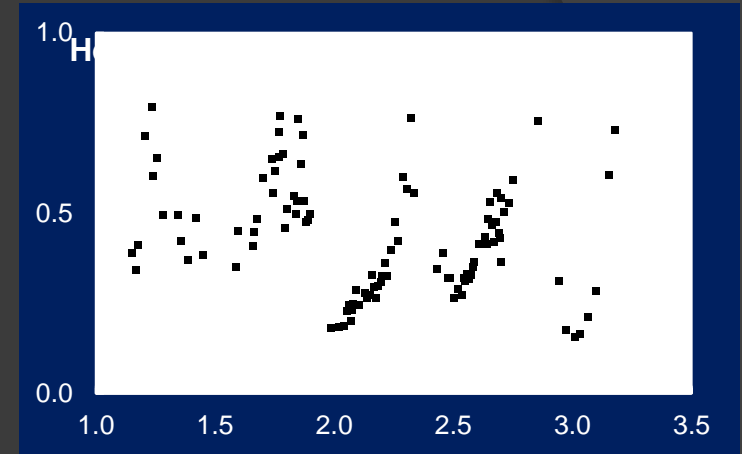
	$\frac{I(6678)}{I(5876)}$	$\frac{I(7065)}{I(5876)}$
Z And	0.57-1.00	0.89-1.07
BF Cyg	0.56-0.95	0.75-1.23
CI Cyg	0.54-0.88	1.00-1.43
AG Dra	0.65-1.14	0.78-0.79
V443 Her	0.86-1.15	0.93-1.20
AG Peg	0.89-1.09	0.73-1.09
AX Per	0.98-1.12	0.80-0.93

Proga & al., 1994

Symbiotiques classiques : $r > 0.5$
 Mesure de la densité électronique

CI Cygni

He I 5876 / He I 6678



Phase orbitale

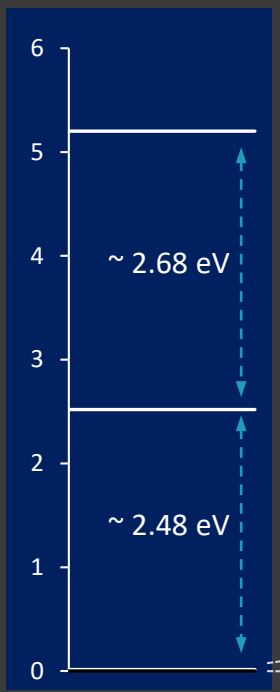
- Siviero & Munari, 2003
- Proga & al., 1994
- Schmid, 1989
- Osterbrock, 1989

Raies excitées par collision

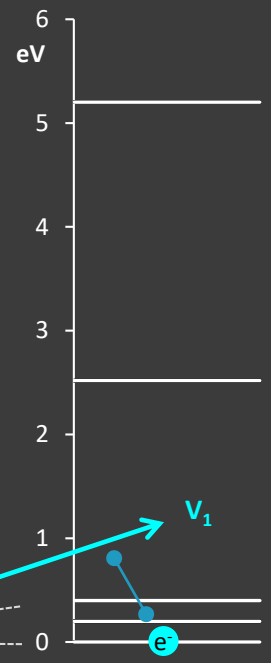
« Raies interdites » = raies excitées par collision

[O III] O²⁺

Niveaux métastables

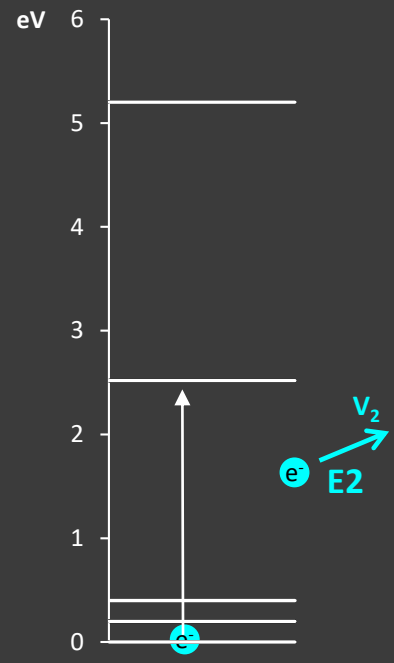


Collision



$$E1 = \frac{1}{2} m v_1^2$$

Transfert d'énergie
Excitation

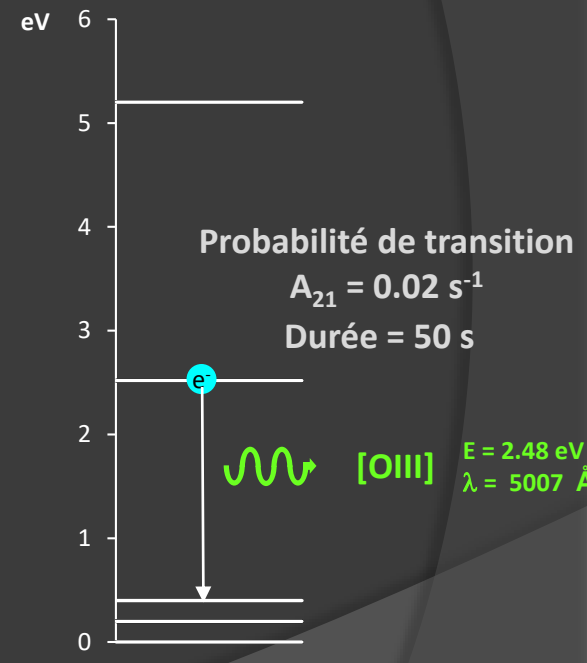


$$E2 = \frac{1}{2} m v_2^2$$

$$E1 - E2 = \frac{1}{2} m (v_1^2 - v_2^2)$$

$$E1 - E2 = 2.48 \text{ eV}$$

Déexcitation
Emission photon



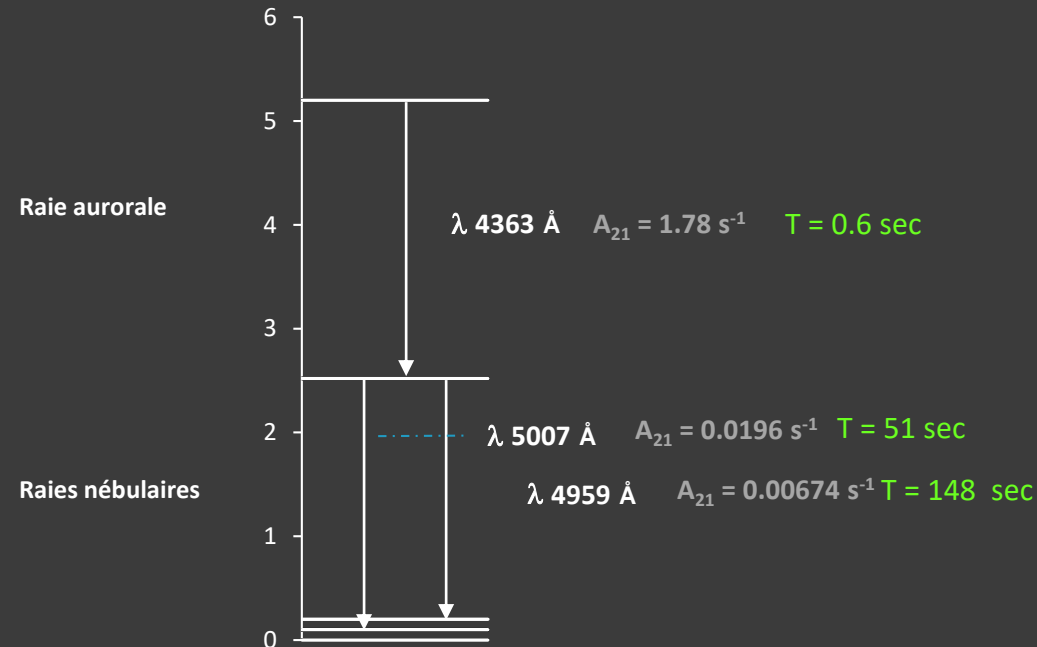
Présence très longue de l'électron sur le niveau métastable
 Dans les conditions habituelles de densités connues sur Terre,
 un électron occupant ce niveau est très rapidement arraché de ce niveau par interaction avec les autres constituants
 → Transition impossible « Raie interdite »

Raies excitées par collision

« *Raies interdites* » = raies excitées par collision

[O III]

O²⁺



$$T_e = \frac{3,29 \cdot 10^4}{\ln([ROIII])/8,3}$$

$$R[OIII] = \frac{I_{5007} + I_{4959}}{I_{4363}}$$

A_{21} = probabilité de transition

Densité critique

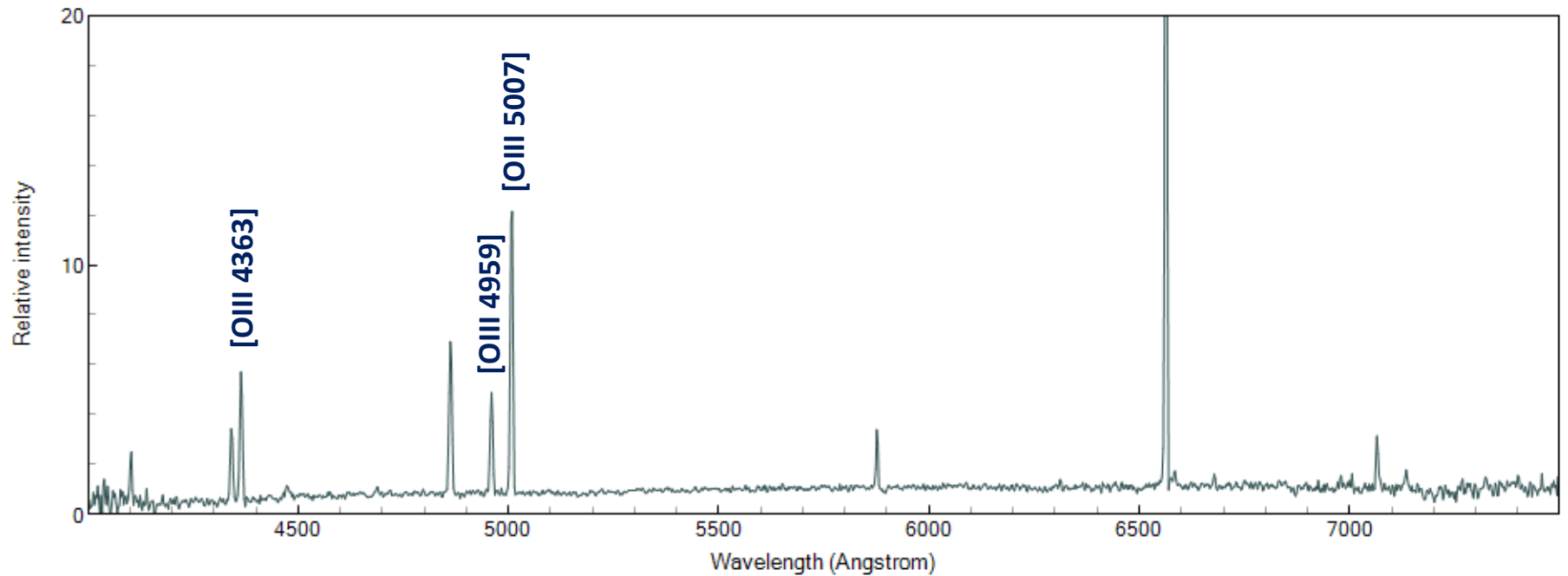
Pour $T_e = 10\ 000\ \text{K}$

Raie	Densité (cm^{-3})
[O I] 6300	$1.4 \cdot 10^6$
[O I] 6363	$4.6 \cdot 10^6$
[O III] 4363	$3.1 \cdot 10^7$
[O III] 4959	$1.7 \cdot 10^5$
[O III] 5007	$5.2 \cdot 10^5$

Raies excitées par collision

V471 Per : symbiotique jaune (Géante K)

V471Per 2016-10-31.885 F Boubault



Raies [O III] intenses

Energie ionisation

Ionization Energy (eV)

	0	+	2+	3+	4+	5+	6+
	I	II	III	IV	V	VI	VII
H	13.6						
He	24.6	54.4					
C	11.3	24.4	47.9	64.5			
N	14.5	29.6	47.4	77.5	97.9		
O	13.6	35.1	54.9	77.4	113.9	138.1	
Ne	24.6	41.0	63.4	97.2	126.2		
Na	5.1	47.3	71.6	98.9	138.4		
Mg	7.6	15.0	80.1				
Al	6.0	18.8	28.4				
S	10.4	23.3	34.9				
Ar	15.8	27.6	40.7	59.6	74.8		
Ca	6.1	11.9	50.9	67.3	84.3		
Fe	7.9	16.2	30.7	54.9	75.0	99.0	125.0
Si	8.1	16.3	33.5	45.1	166.8		

Relation empirique

Température composant chaud

$$T_h = X_i * 1000$$

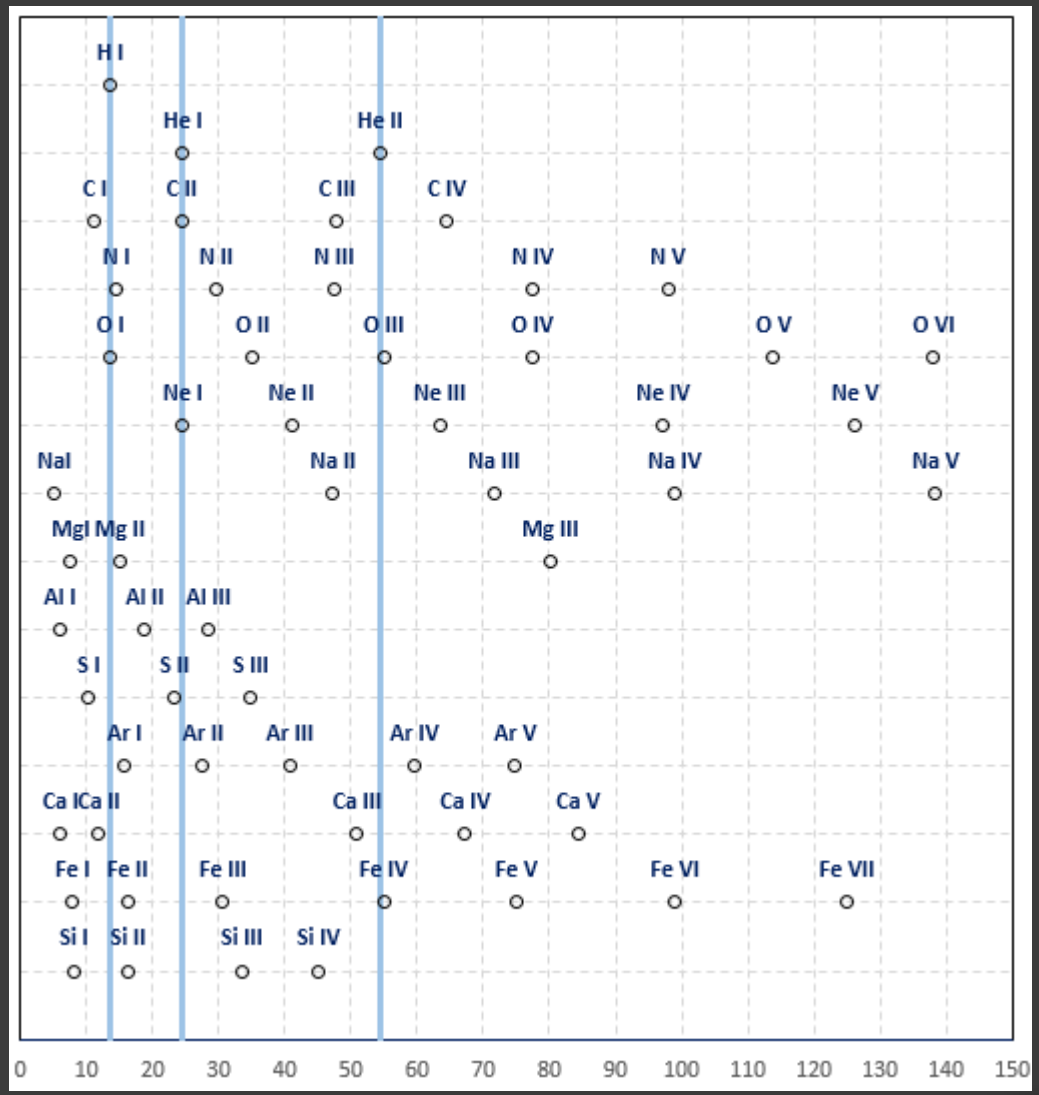
T_h = température en K

X_i = potentiel ionisation le plus élevé (en eV)

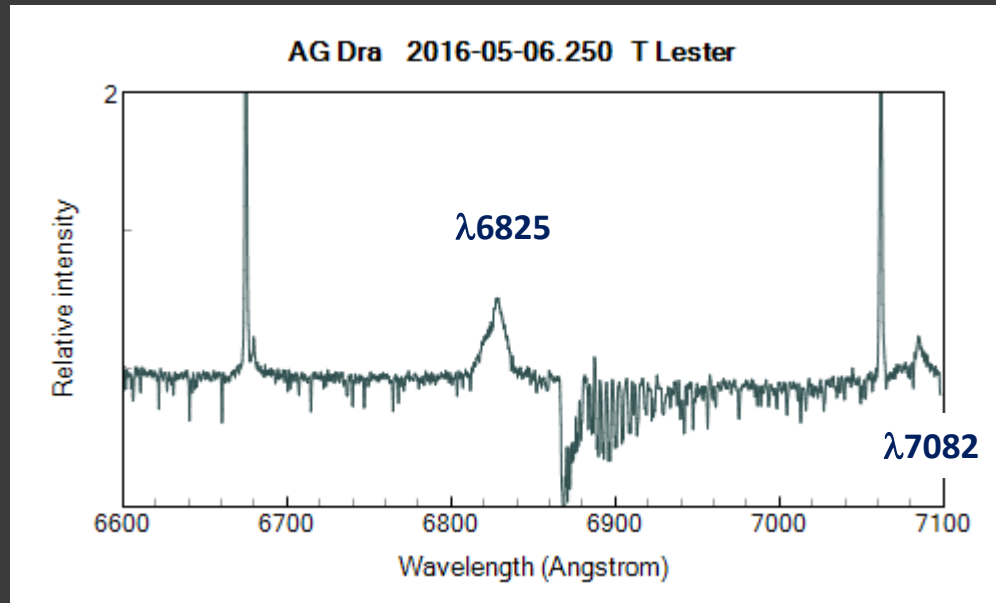
Mürset & Nussbaumer, 1994

Raie	T_h
H I	15000
He I	25000
He II [O III]	55000
[Fe VII]	125000
O VI	140000

Raies excitées par collision

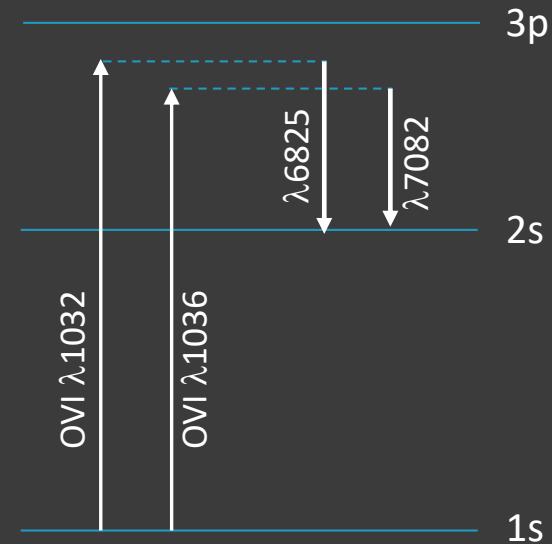


Raman OVI



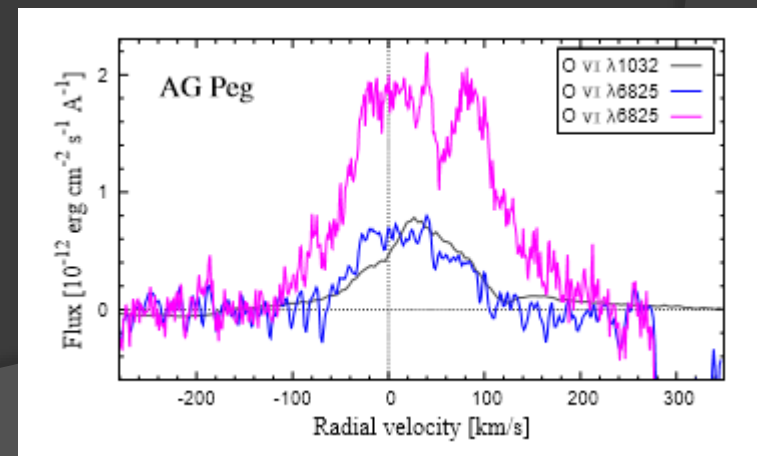
Raman scattering
doublet OVI
1032 1036
par Hydrogène neutre

Schmid 1989

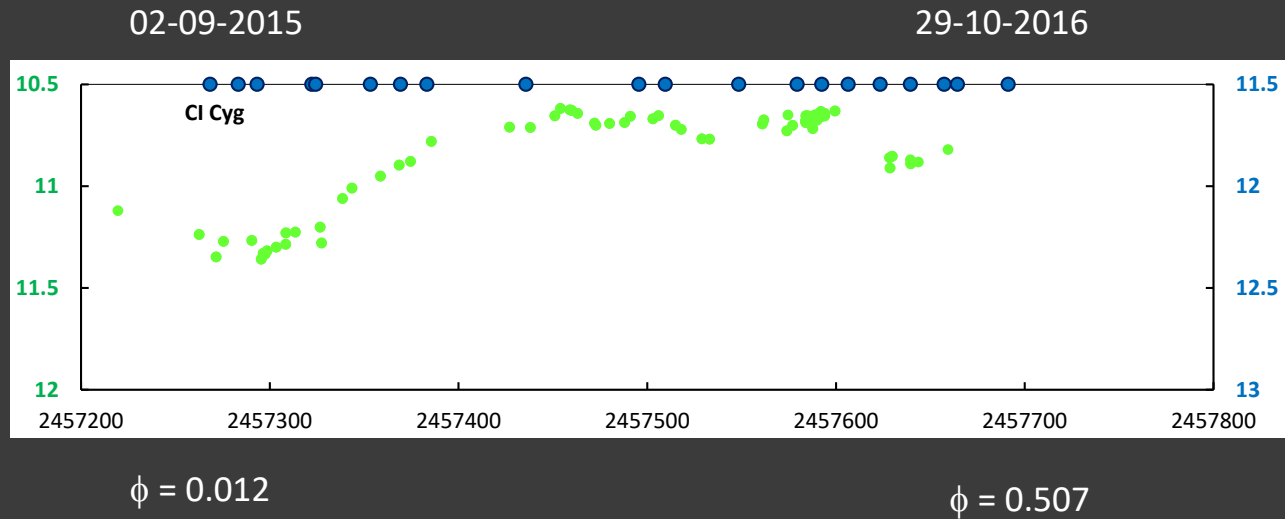


Raies caractéristiques des symbiotiques

1. Présence de bandes d'absorption caractéristiques d'une géante de type tardif (late-type giant), parmi lesquelles TiO, H₂O, CO, CN, VO ainsi que des lignes d'absorption telles que CaI, CaII, FeI, NaI
2. Présence de fortes raies d'émission HI, HeI et ...
- raies d'émission d'ions tels [OIII] (potentiel d'ionisation > 35 eV)
- [...]
3. La présence d'une bande $\lambda = 6825$, même si les bandes de l'étoile froide n'apparaissent pas.



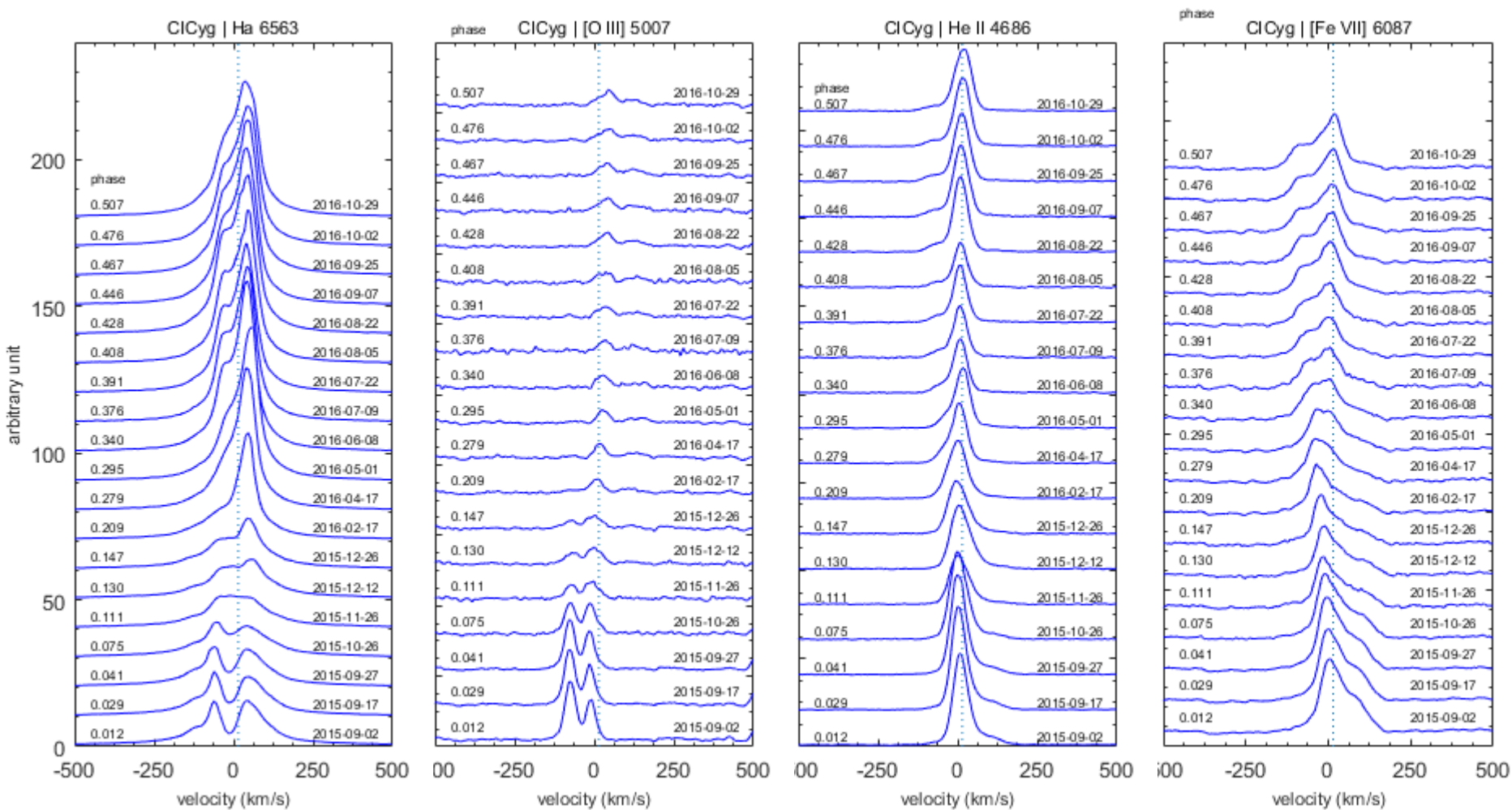
Variations orbitales : CI Cygni



E0 = 2442690
P = 853.8 jours
Fekel & al., 2000

Spectres eshel
F. Teyssier

Variations orbitales : CI Cygni

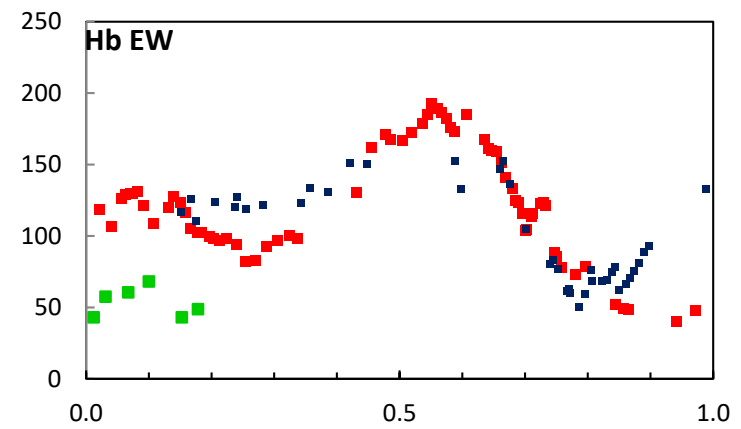
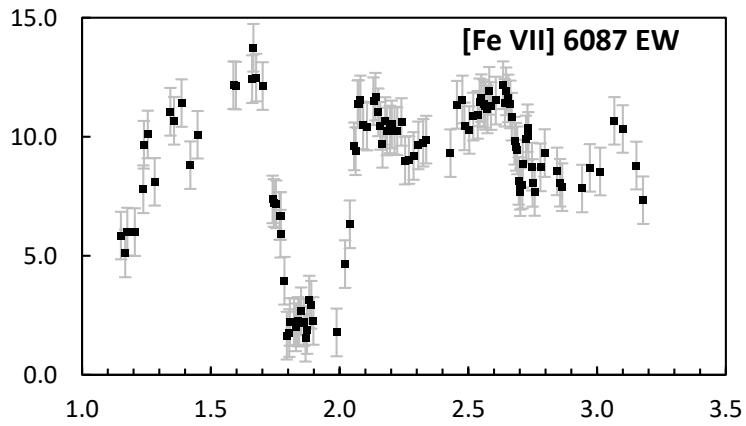
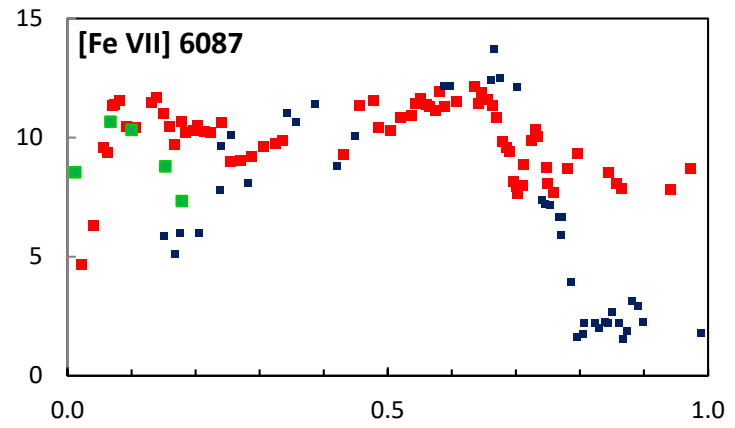
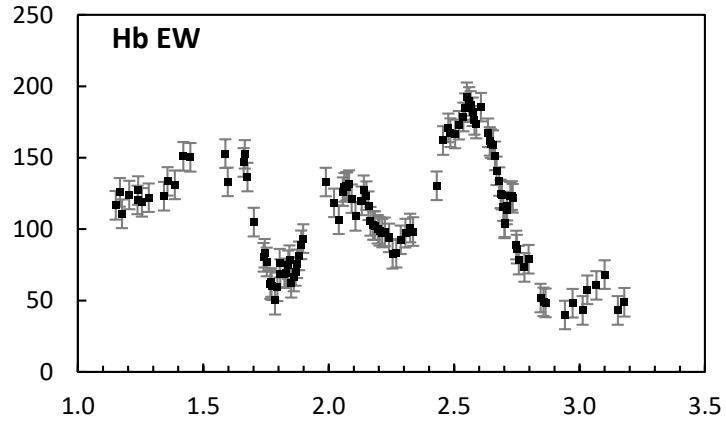


Variations orbitales
Activité

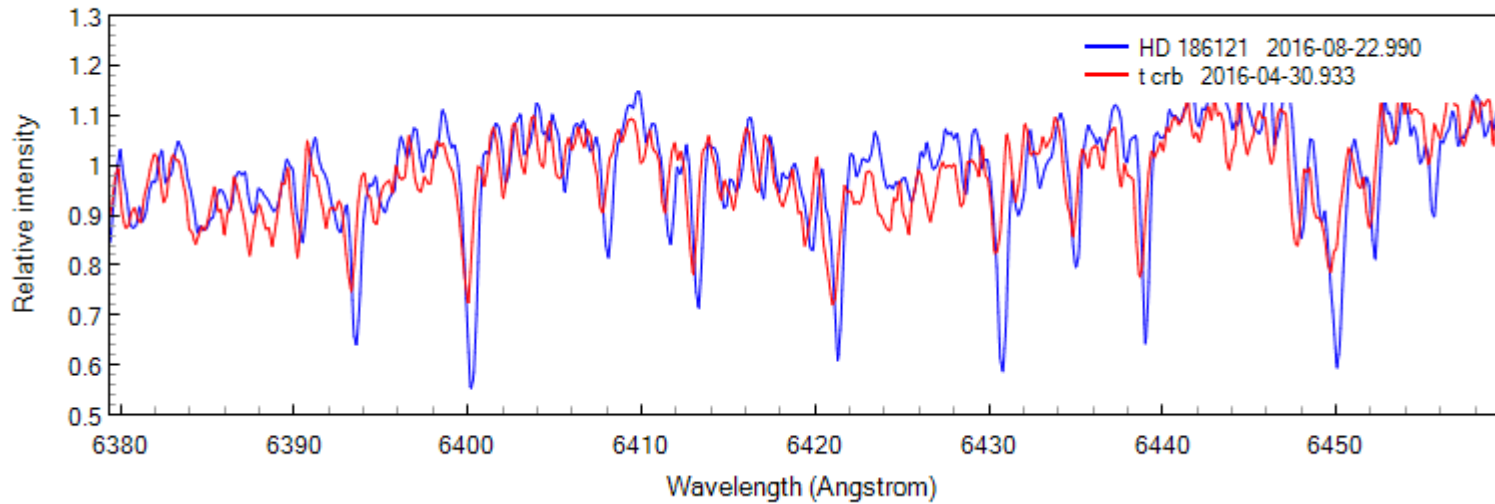


Suivi sur +++ orbites

Variations orbitales : CI Cygni



HD 186121 2016-08-22.990 fteyssier



$$V_r = \frac{\Delta\lambda}{\lambda} c$$

Ephéméride
Fekel et al., 2000

JD 0 2447918.62

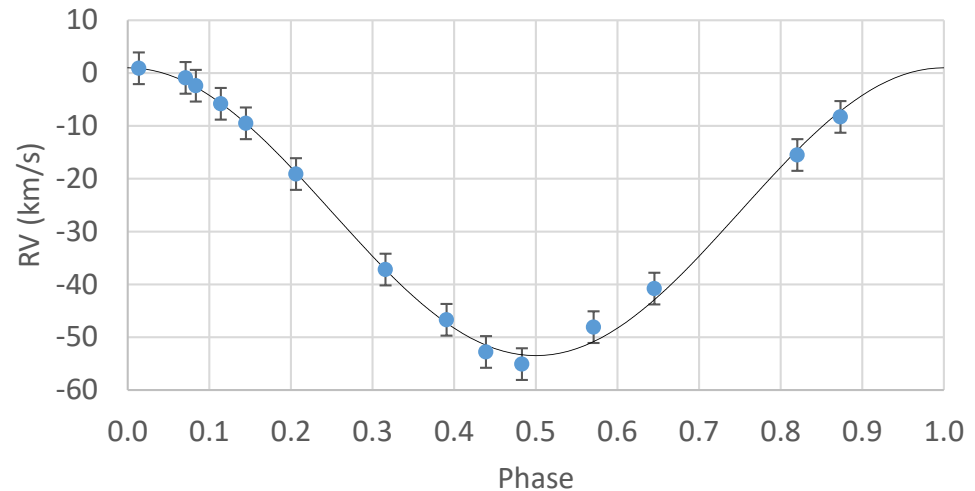
E 227.57 d

Vitesse GR $K_1 = 27.2 \text{ km.s}^{-1}$

Vitesse système $\gamma = -26.2 \text{ km.s}^{-1}$

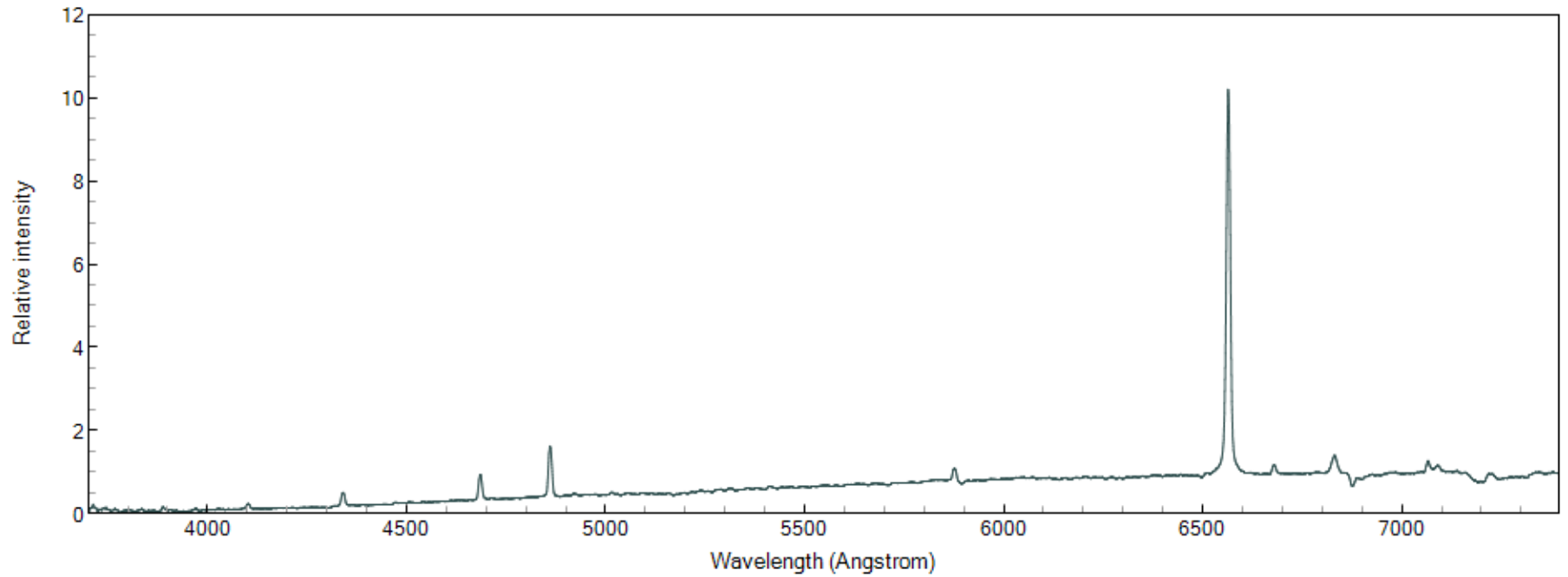
Incertitude ~

T CrB radial velocity (2016)



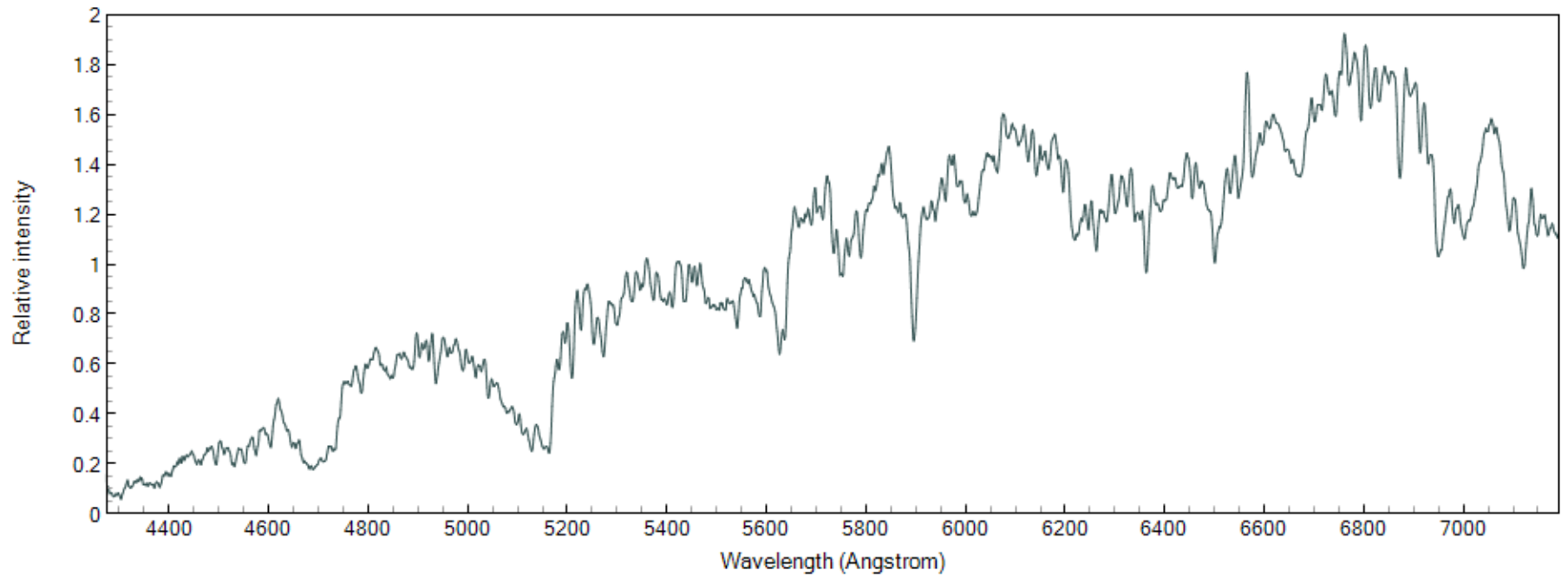
- 1 Spectroscopie et Classification spectrale
- 2 La découverte des Etoiles Symbiotiques
- 3 Modèle d'une Etoile Symbiotique
- 4 Formation du spectre
- 5 Les Symbiotiques à l'état calme
- 6 **Le Zoo des Symbiotiques**
- 7 Les Symbiotiques en Outburst
- 8 Contribution des amateurs

AG Dra 2016-10-06.910 Jacques Montier



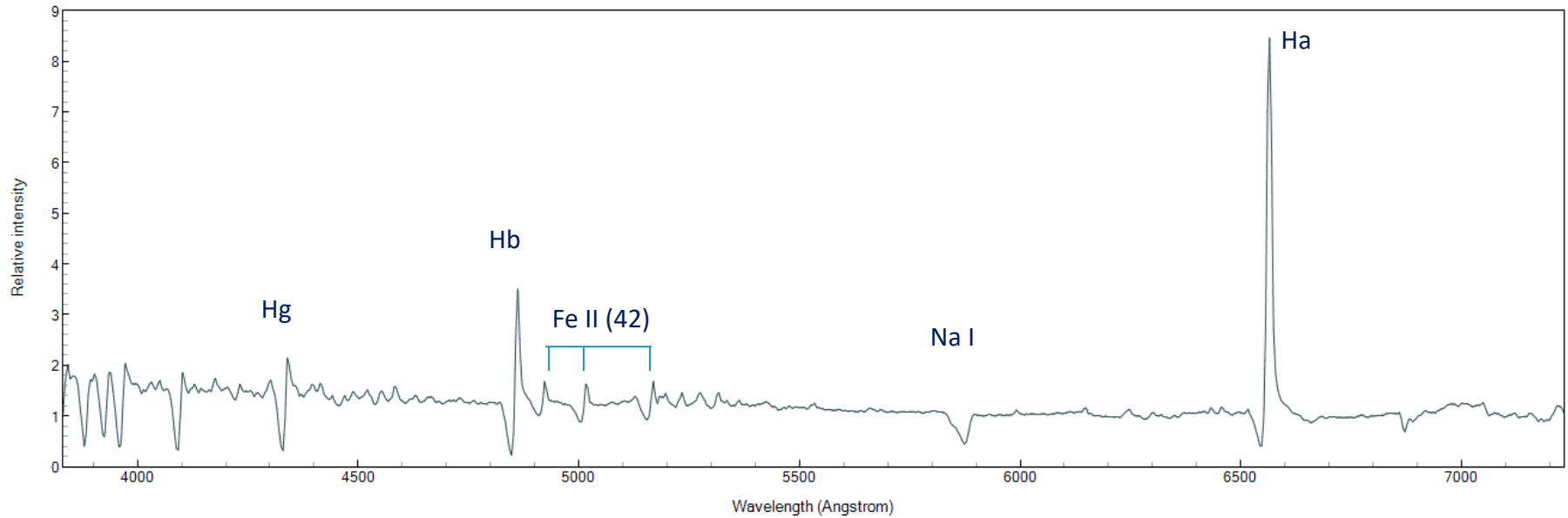
Géante carbonée : NQ Gem

NQ Gem 2015-10-24.089 P. Somogyi

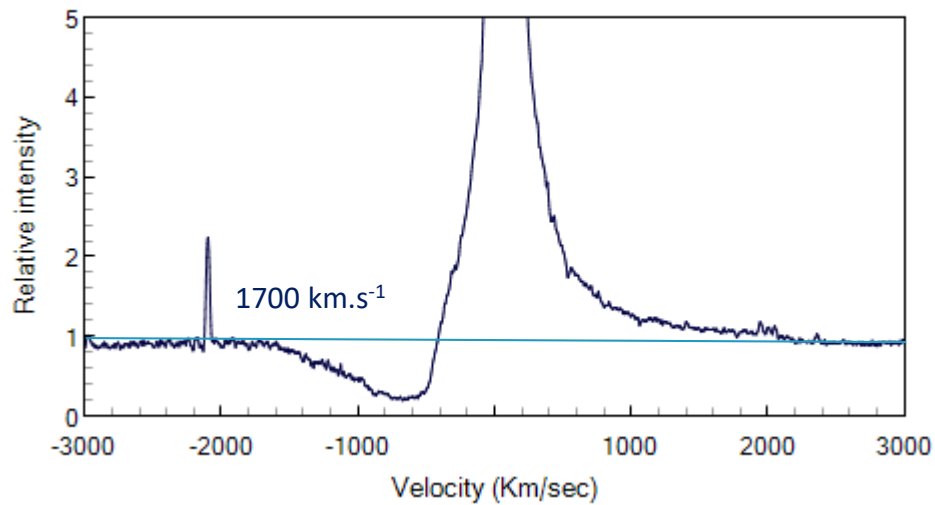


Jet collimaté : V694 Mon

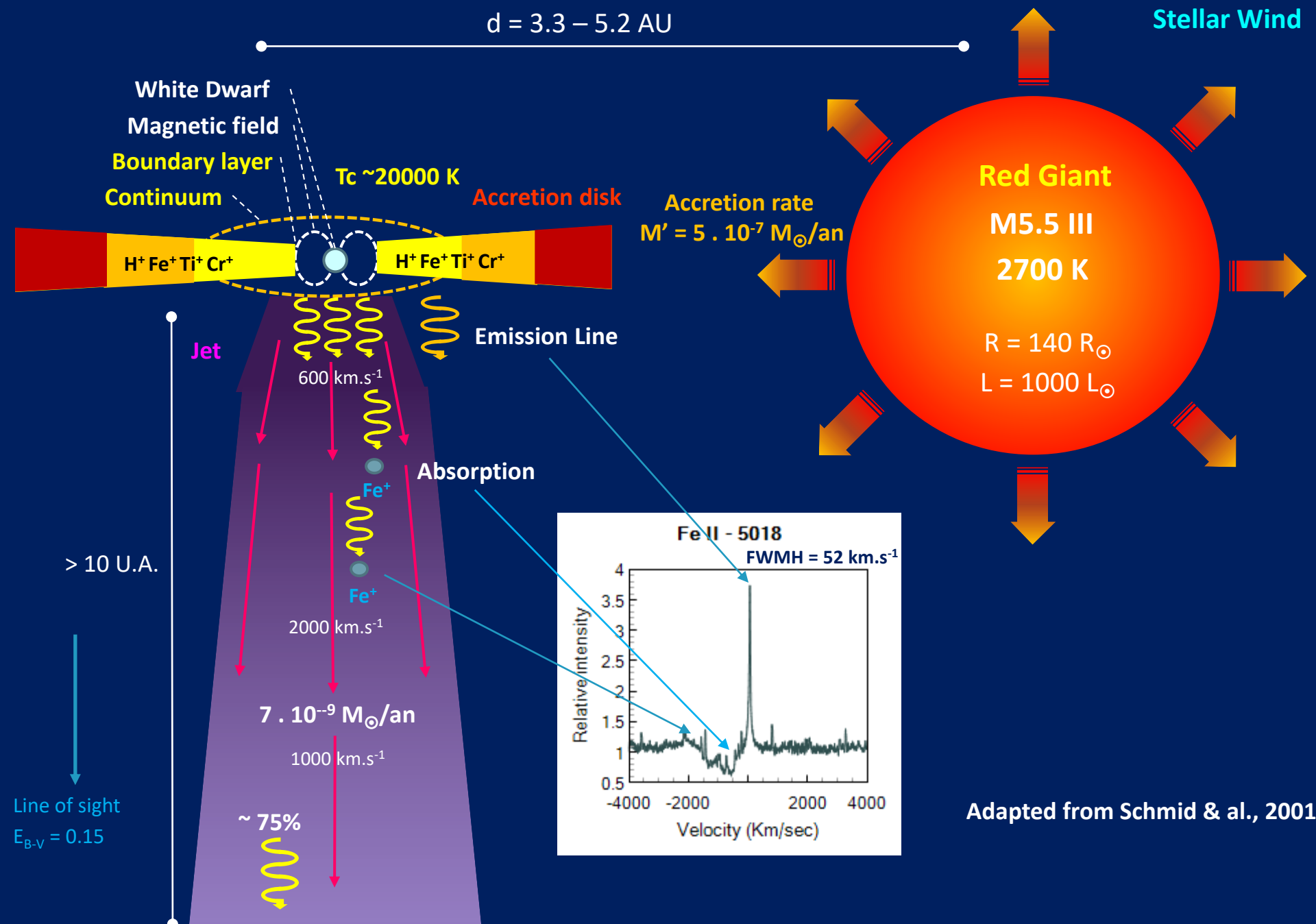
V694 Mon 2017-02-16.854 LFranco



H α - V694 Mon 2017-02-17.860 4947 s (8 x 600 s) fteyssier



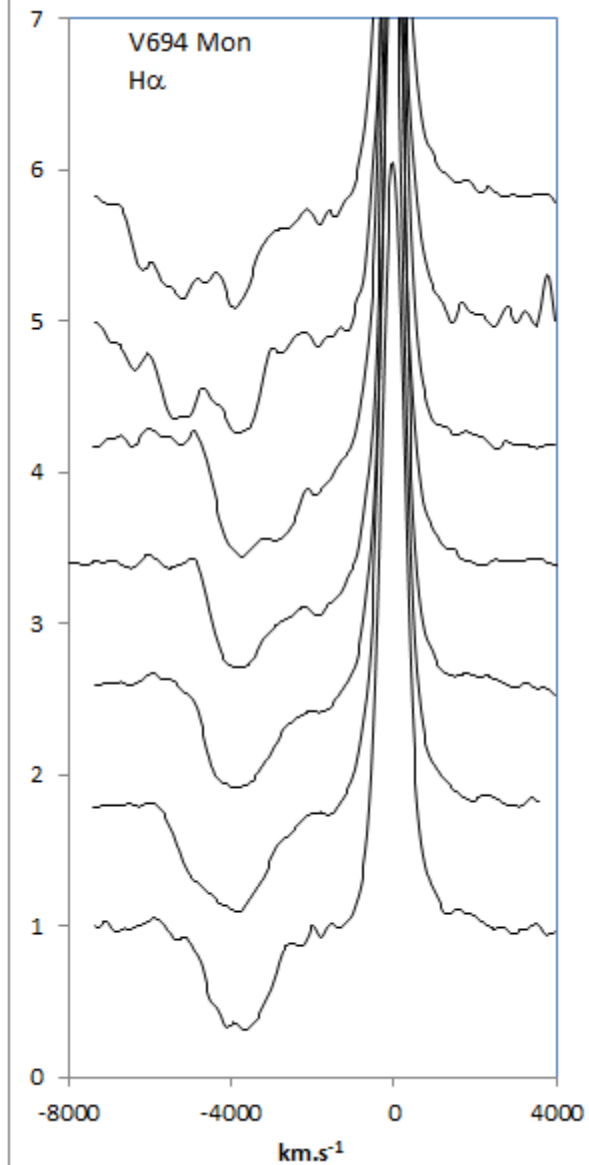
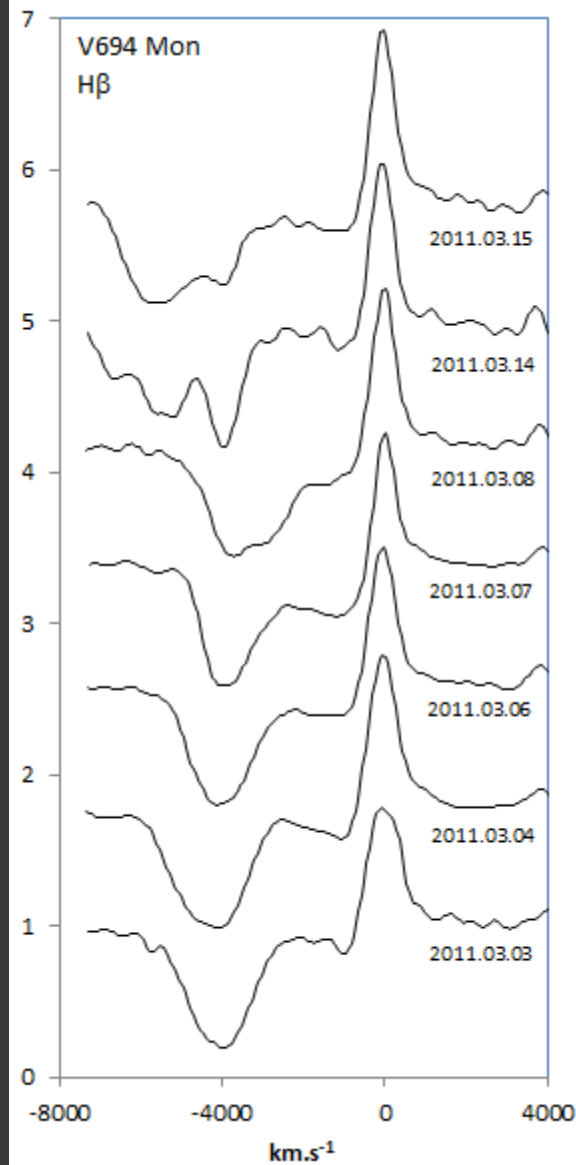
Jet collimaté : V694 Mon

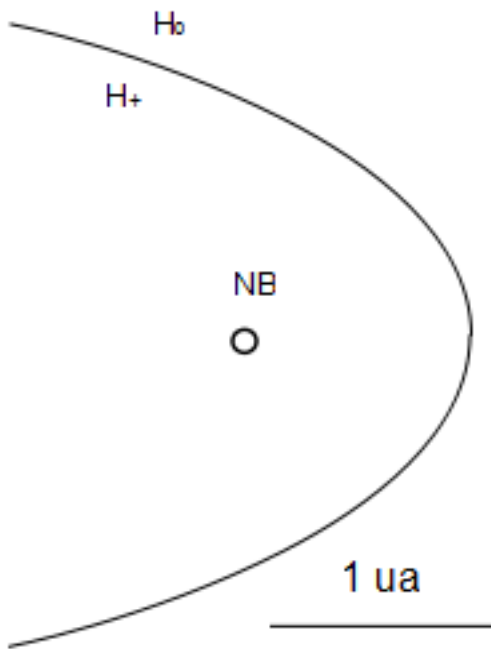


Jet collimaté : V694 Mon

Mars 2011
LISA R = 1000

High state



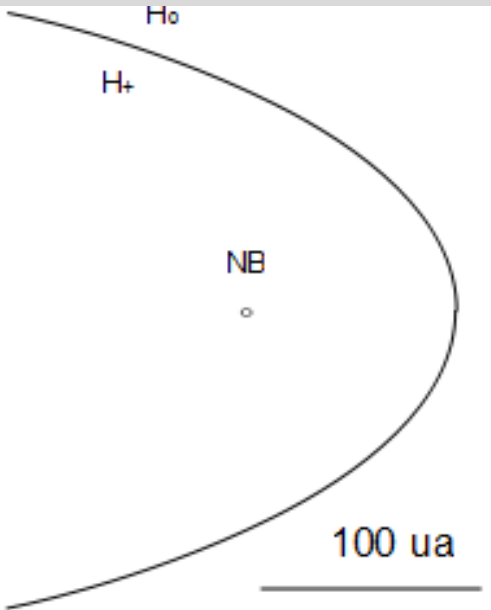


Type S (« star »)

80 % des symbiotiques
 Géante rouge normale
 Période orbitale de 200 à 800 j



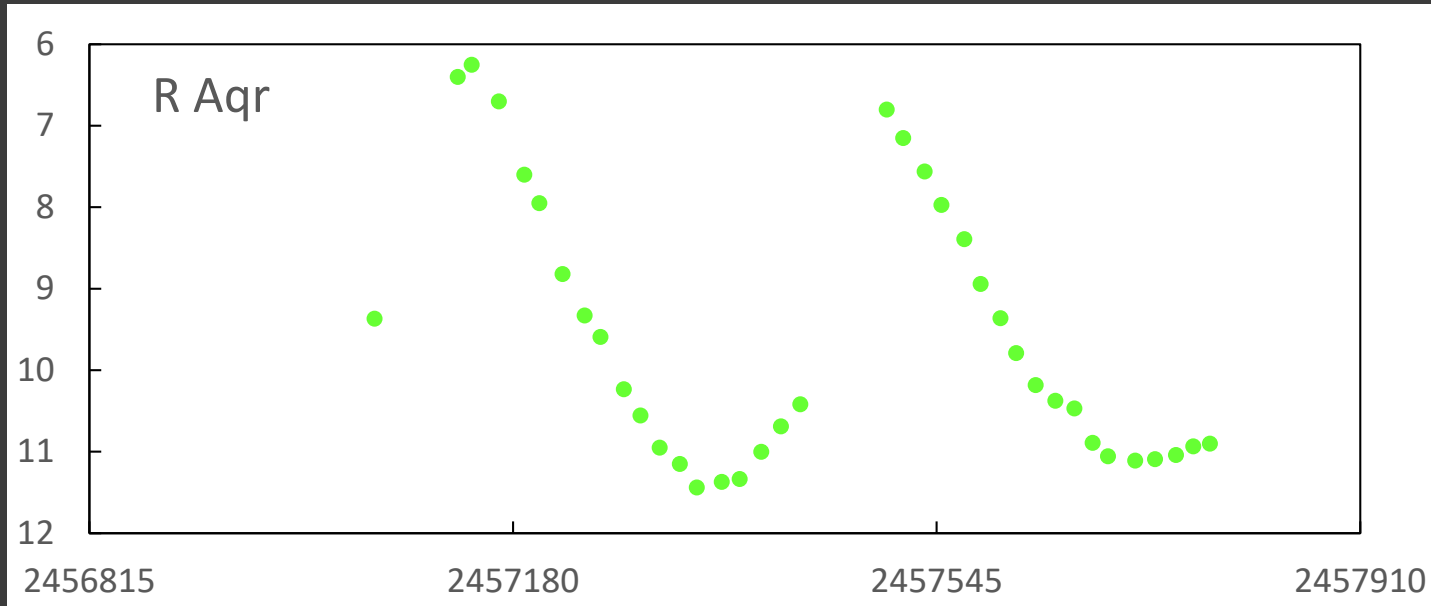
2 types de symbiotiques



Type D (« dust »)

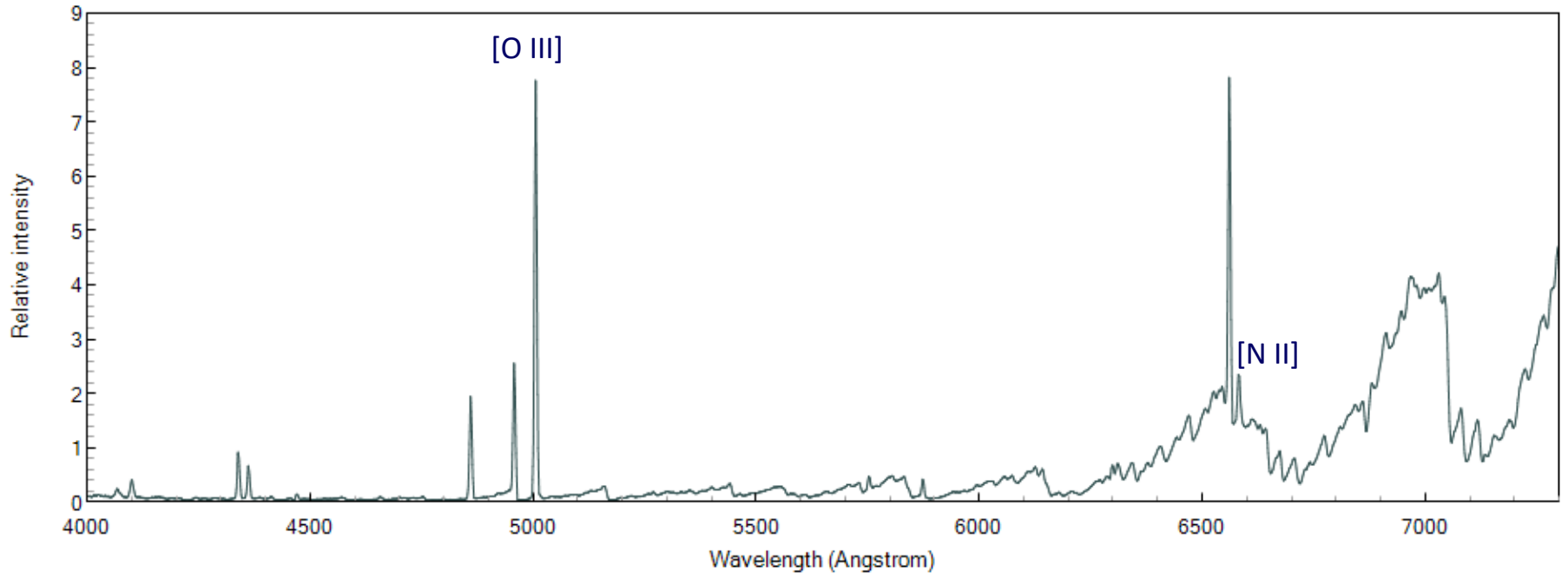
20 % des symbiotiques
 Géante rouge de type Mira
 Période orbitale de +++ 1000 jours
 Nuage de poussières
 caractéristique dans l'infrarouge





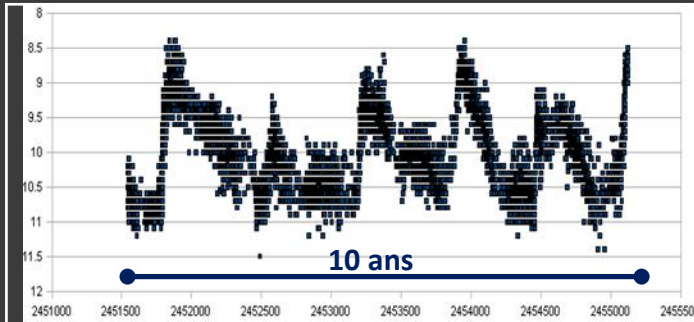
$\Delta \text{ mag V} \sim 4$
 $P \sim 387 \text{ jours}$

R Aqr 2011-11-23.832 C. Buil



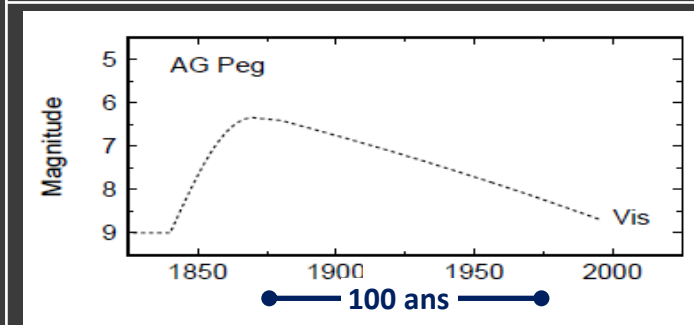
- 1 Spectroscopie et Classification spectrale
- 2 La découverte des Etoiles Symbiotiques
- 3 Modèle d'une Etoile Symbiotique
- 4 Formation du spectre
- 5 Les Symbiotiques à l'état calme
- 6 Le Zoo des Symbiotiques
- 7 Les Symbiotiques en Outburst
- 8 Contribution des amateurs

2 types d'outbursts



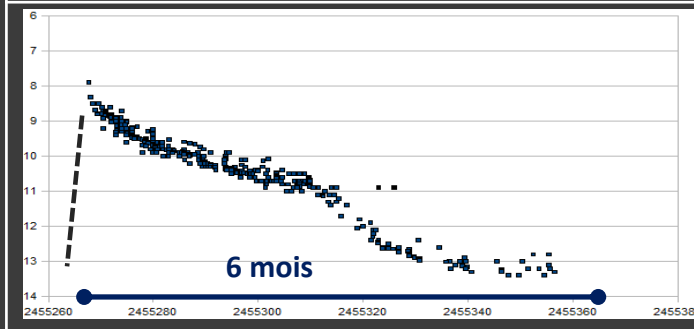
Type Z And
ou outburst de symbiotique classique
Z And, CI Cyg

Outbursts d'amplitude moyenne (2-3 mags) parfois en série, espacés de périodes calmes



Novae Symbiotiques
AG Peg, V1016 Cyg, HM Sge

Phénomène de type nova (très lente) s'étendant sur des décennies



Novae Récurrentes de type symbiotique
RS Oph, T CrB

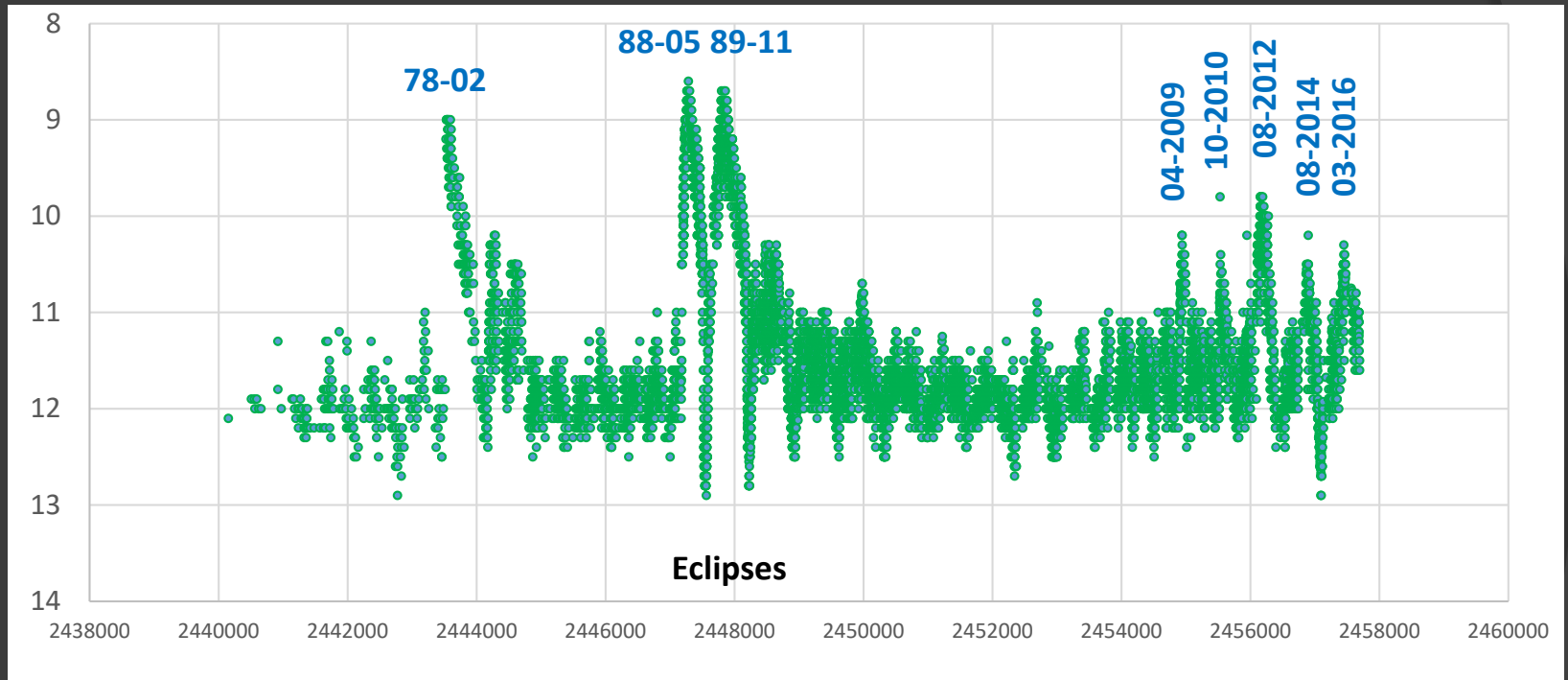
Phénomène de type nova se reproduisant à des échelles de temps de l'ordre de la décennie

Rem : certaines symbiotiques n'ont jamais présenté d'outbursts
d'autres sont considérées comme étant en outburst permanent

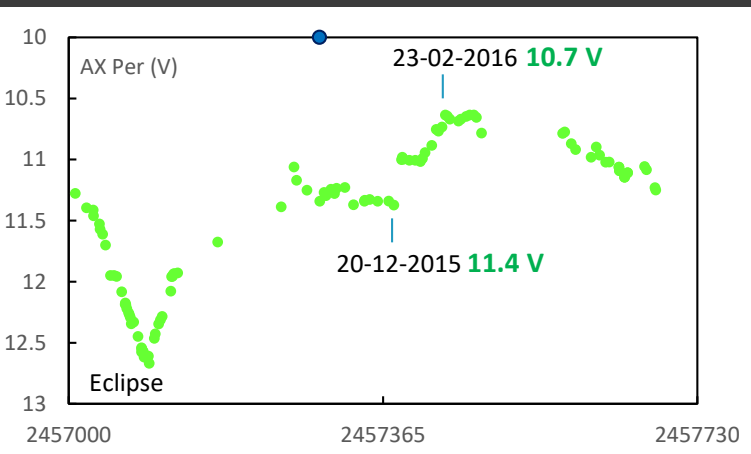
EG And V443 Her UV Aur
V694 Mon

Outburst Symbiotuque AX Per

AX Per Courbe de luminosité V+Vis 1968-2016 – AAVSO (17000 observations)



Outburst AX Per 2015-2016

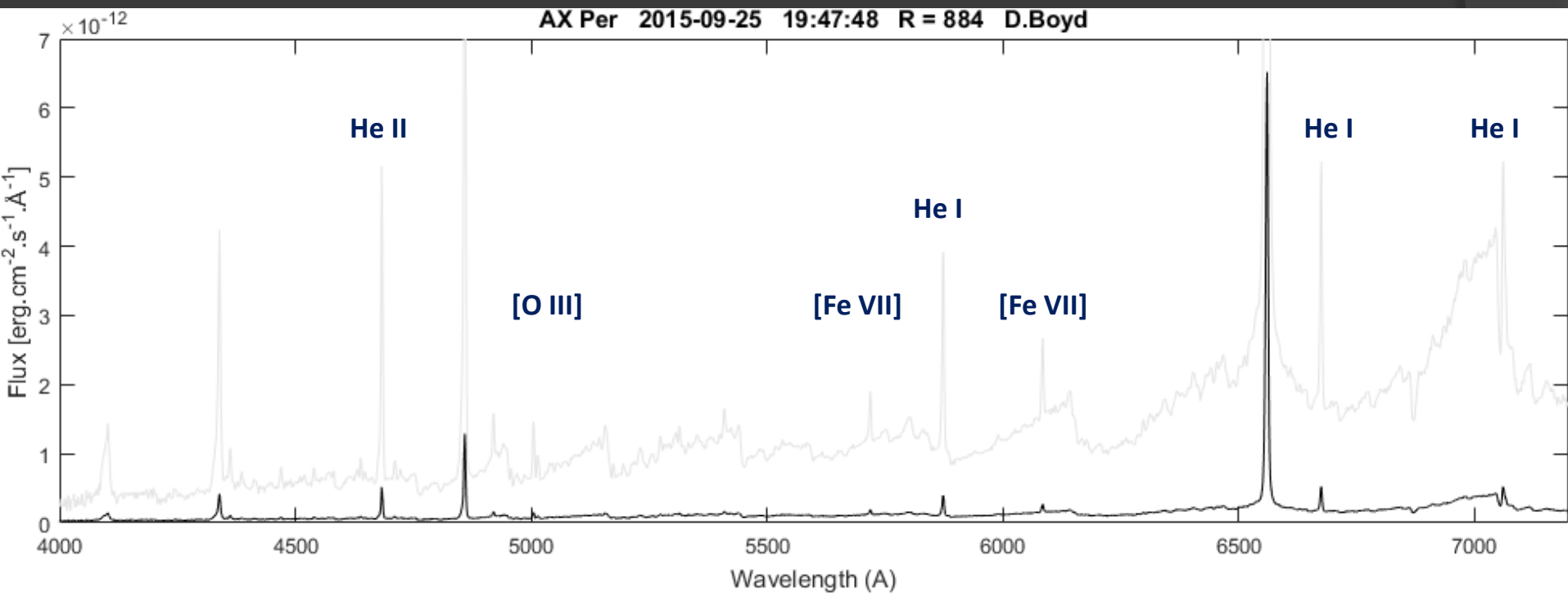


AX Per Etat calme

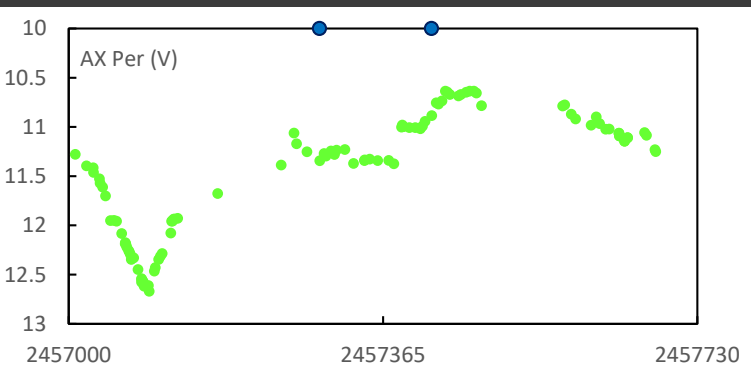
D Boyd

25-09-2016

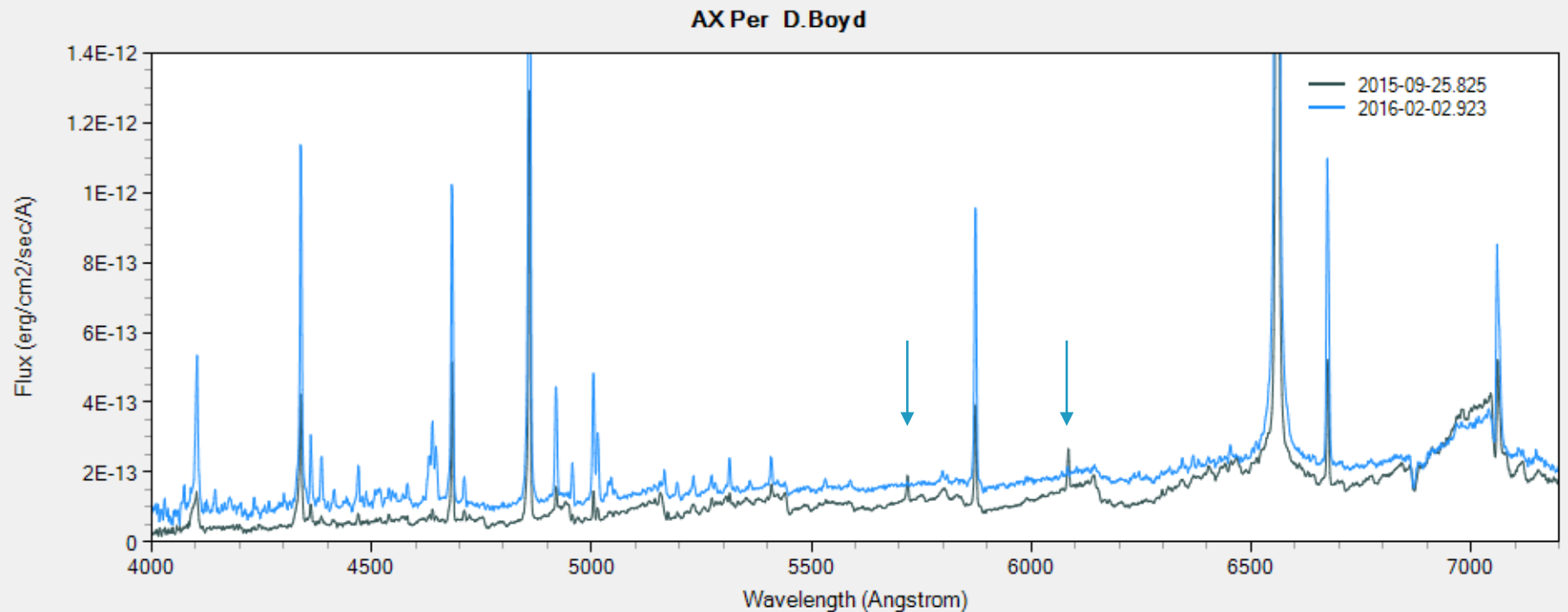
R = 1000 (LISA)



Outburst AX Per 2016



Bandes absorption TiO ↓
Intensité des émissions ↑
Raies de forte ionisation ↓



- Diminution de la température composant chaud ou rayonnement UV masqué
- Augmentation du volume ionisé de la nébuleuse

Un modèle
Formation d'un disque d'accrétion

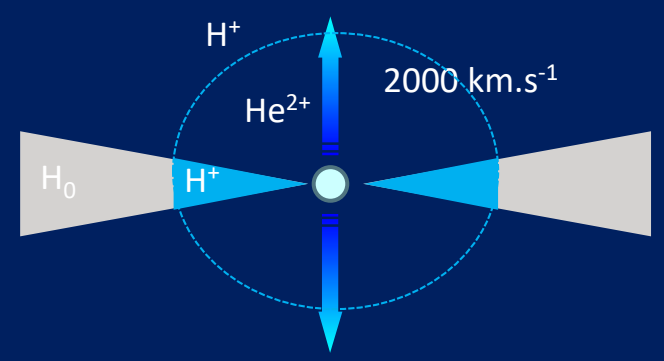
Nébuleuse

$T_e = 15\ 000\ K$
 $N = 6-9 \cdot 10^9\ cm^{-3}$

$d = 1-5\ U.A.$

Vent Stellaire
 $\dot{M}' = 3 \cdot 10^{-6}\ M_{\odot}/an$

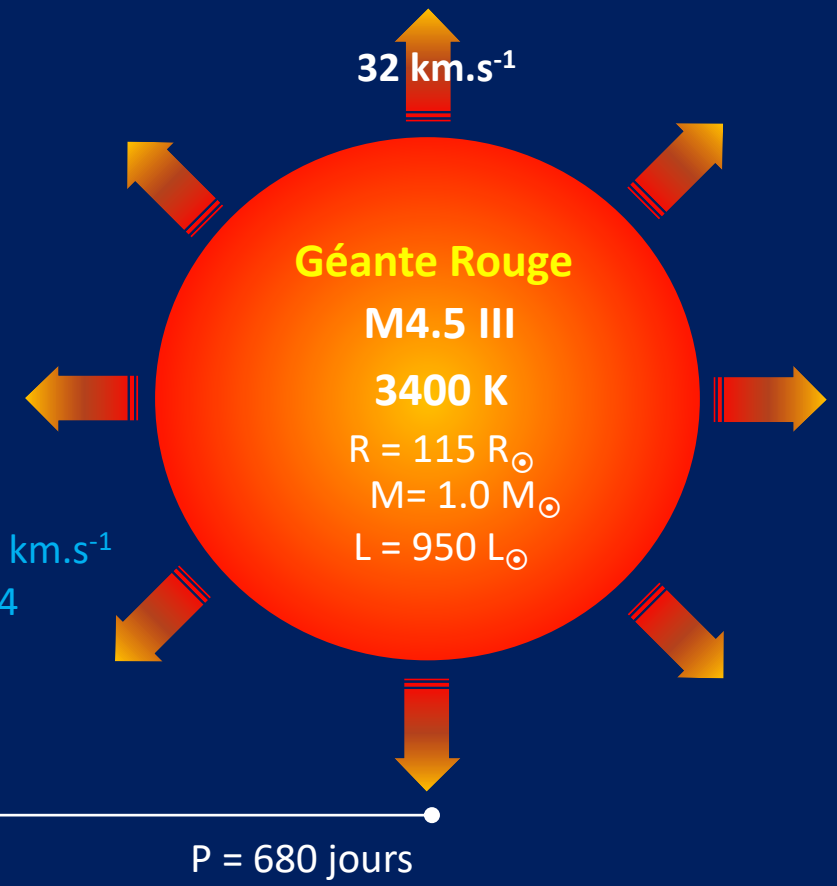
$\dot{M}' = 2-3 \cdot 10^{-6}\ M_{\odot}/an$



Naine Blanche

$110\ 000\ K$
 $R = 0.018\ R_{\odot}$
 $M = 0.4\ (0.1)\ M_{\odot}$
 $L = 314\ L_{\odot}$

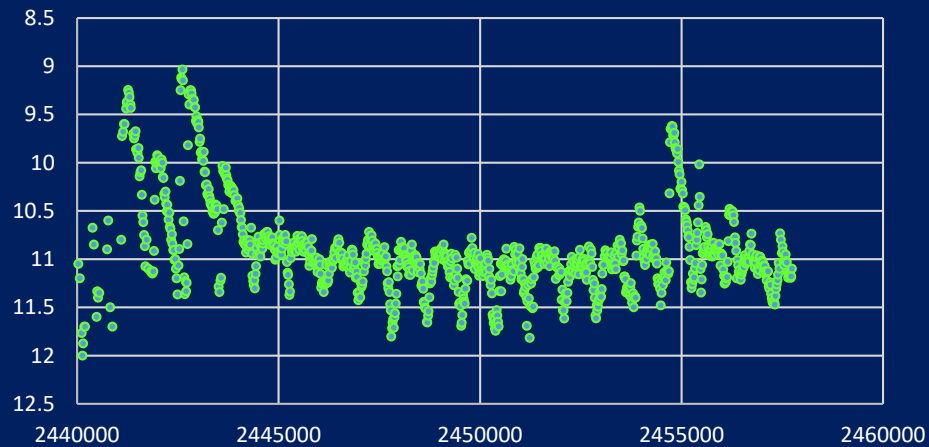
$V_r = -110\ km.s^{-1}$
 $E_{B-V} = 0.24$



$d = 3.6\ RG$

$d = U.A.$

$P = 680\ jours$



Teyssier, JAAVSO Volume 39, 2011

41

CI Cygni 2010 Outburst and Eclipse: An Amateur Spectroscopic Survey—First Results From Low Resolution Spectra

François Teyssier

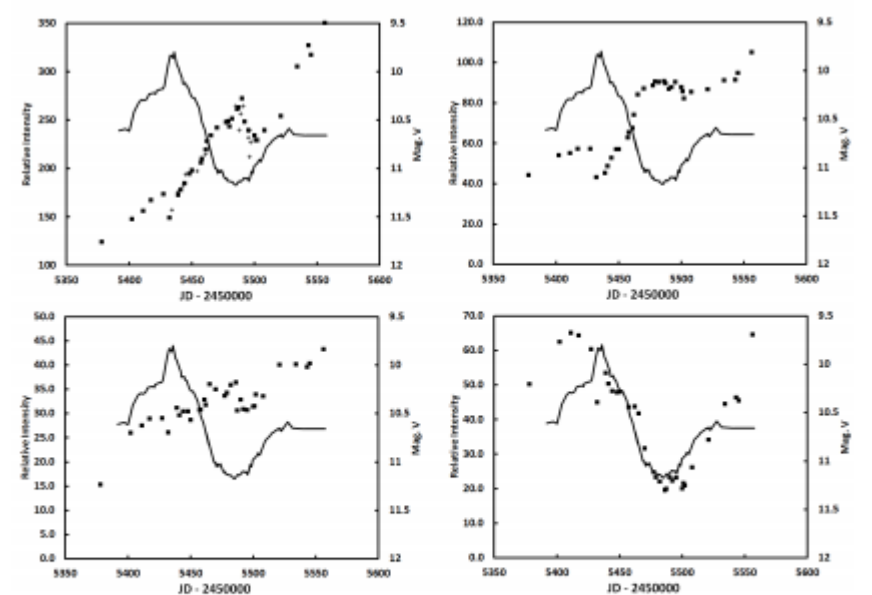


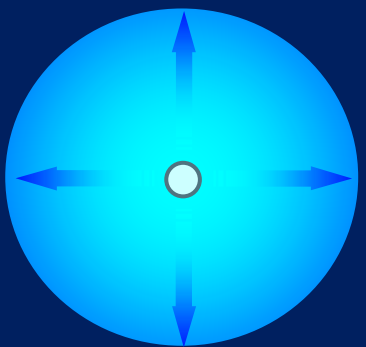
Figure 10. Equivalent widths time series (JD 2450000). Squares for low resolution values, crosses for eShell values (only H α). Figure 10a (top left): H α equivalent width. Figure 10b (top right): H β equivalent width. Figure 10c (bottom left): He I λ 5876 equivalent width. Figure 10d (bottom right): He II λ 4686 equivalent width.

Un modèle
Expansion enveloppe

Naine Blanche

Etat calme

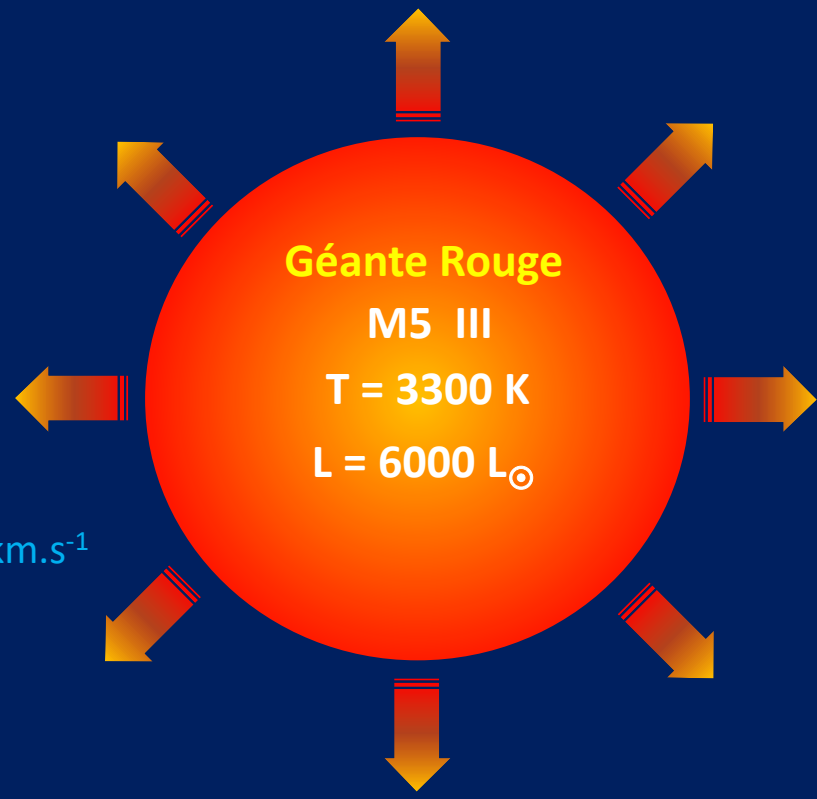
125 000 K
 $R = 0.06 R_{\odot}$
 $L = 560 L_{\odot}$



Outburst

6900 K
 $R = 28 R_{\odot}$
 $L = 15000 L_{\odot}$

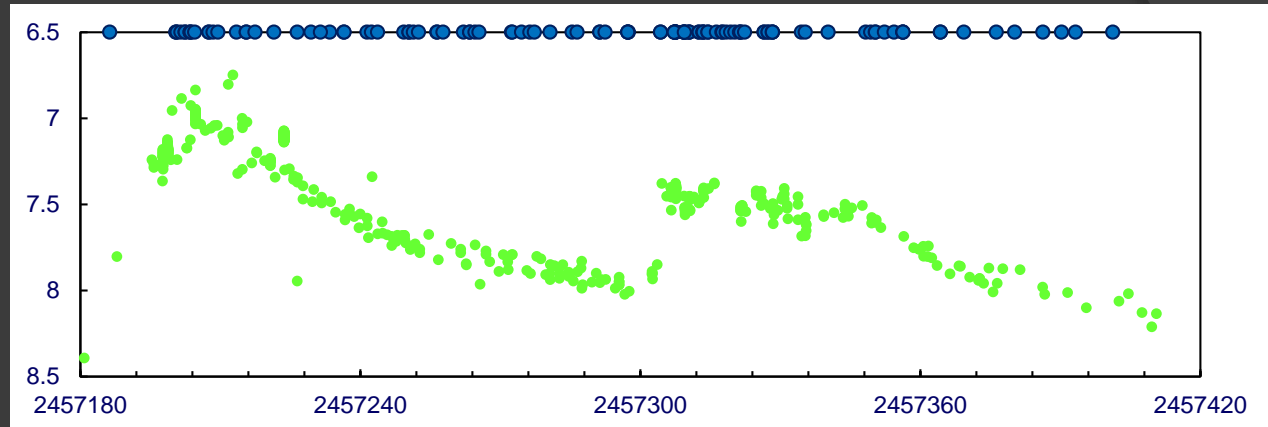
$V_r = +15 \text{ km.s}^{-1}$
 $E_{B-V} = 0.4$



Géante Rouge
M5 III
T = 3300 K
L = 6000 L_⊙

P = 855 jours

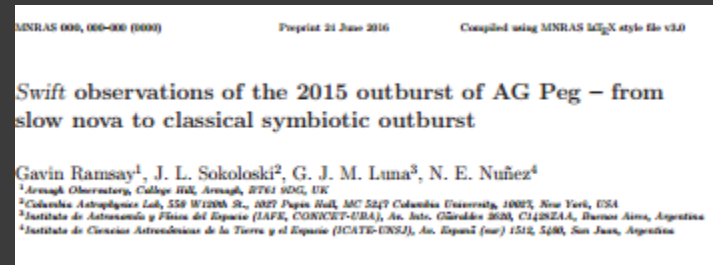
Outbursts symbiotiques AG Peg 2015



Many groups, including amateur astronomers³, have made spectroscopic observations of AG Peg over its outburst. These observations show strong emission lines, including the Balmer series plus He I (6678) and He II (4686), [O III] (4363) and the O vi emission band at 6825 Å, which is due to Raman scattering. A full analysis of the optical spectra made over the course of the outburst is beyond the scope of this work, but we were able to estimate the effective temperature of the ionizing source using the He II (4686) and H β lines and the formula of Iijima (1981) (quoted in Sokoloski et al. 2006) which derives the effective temperature using the equivalent width (EW) of these lines (we ignore the He I (4471) line since it is much weaker than He II and H β). We used spectra taken by amateur astronomers⁴ which covered the He II (4686) and H β lines to derive their EW (we estimated that the error on the EW measurements was ~ 10 percent by making a number of measurements of the same line).

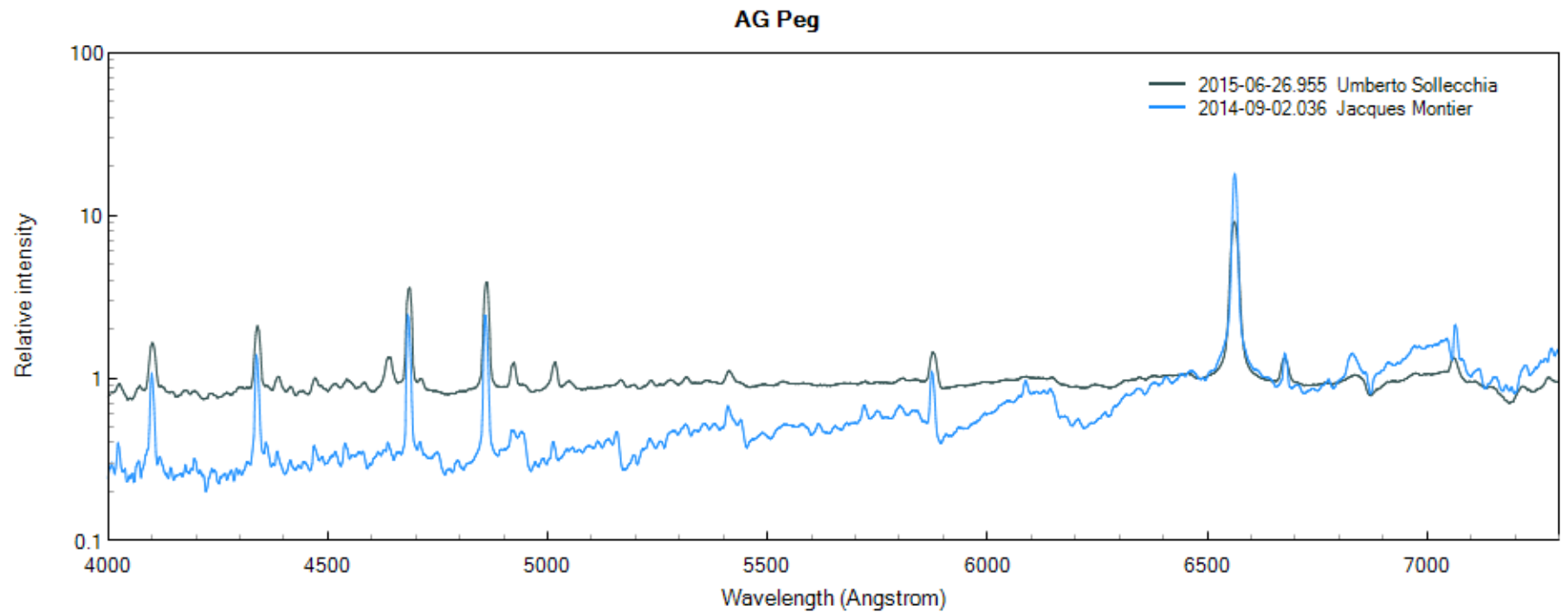
³ e.g. <http://www.astronomie-amateur.fr>

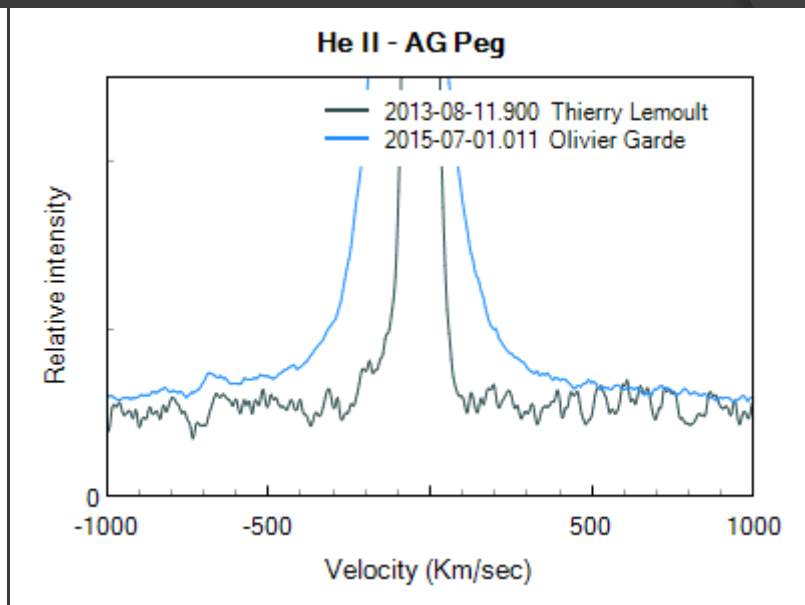
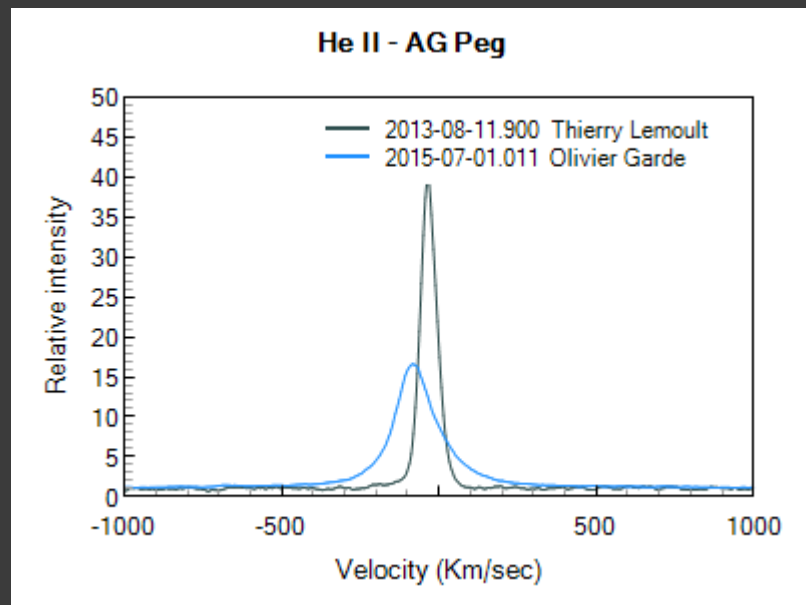
⁴ http://www.astrosurf.com/aras/Aras_DataBase/Symbiotics/AGPeg.htm



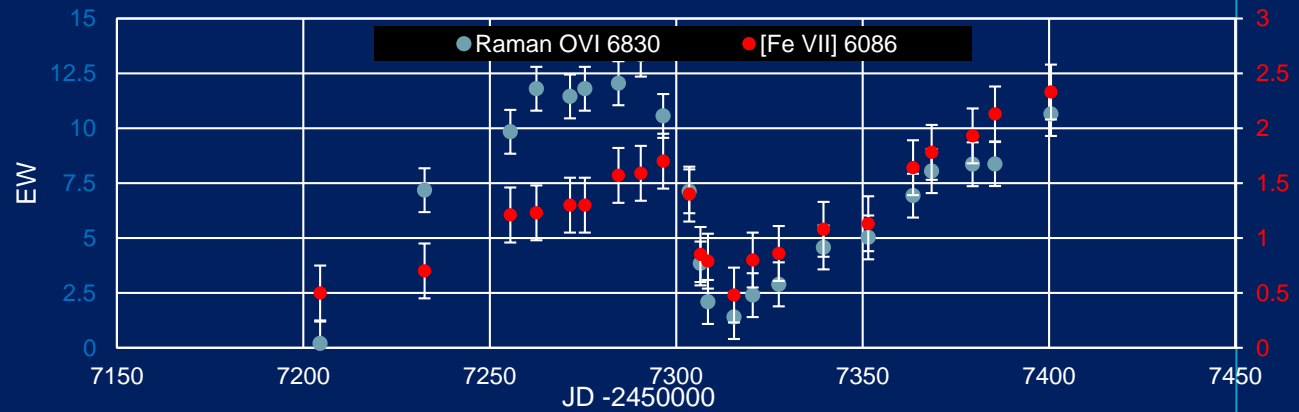
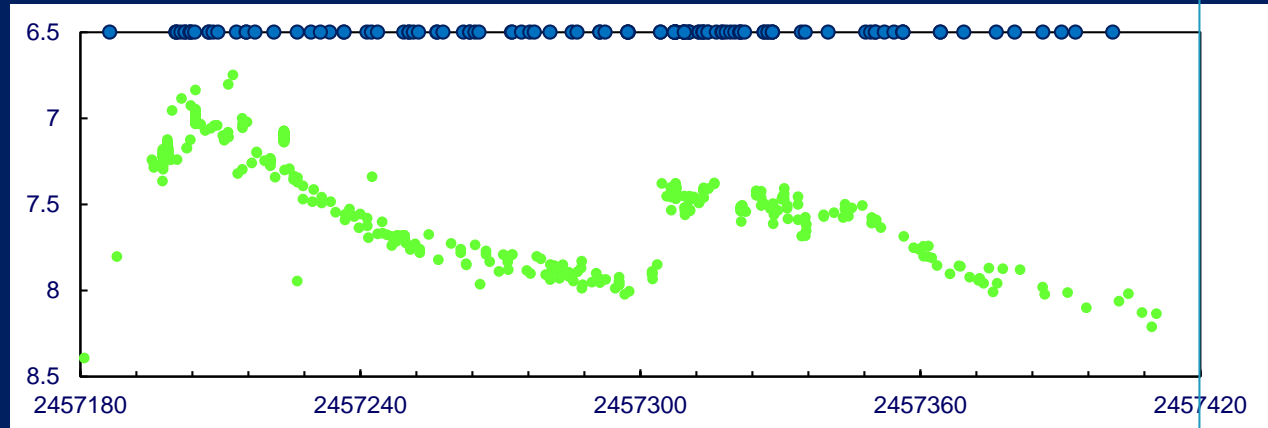
We also thank François Teyssier for altering us to the many amateur spectroscopic observations which have been made and we acknowledge and thank François Teyssier, Umberto Sollecchia, Joan Guarro Flo, Jacques Montier, Peter Somogyi, Keith Graham and V Bouttard for use of their spectra.

Outbursts symbiotiques AG Peg 2015



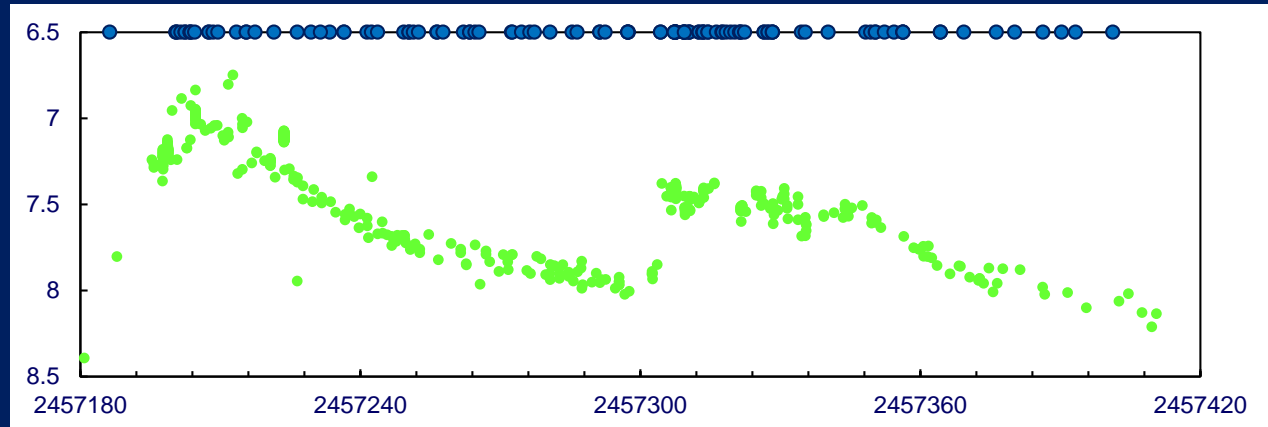


Outbursts symbiotiques AG Peg 2015



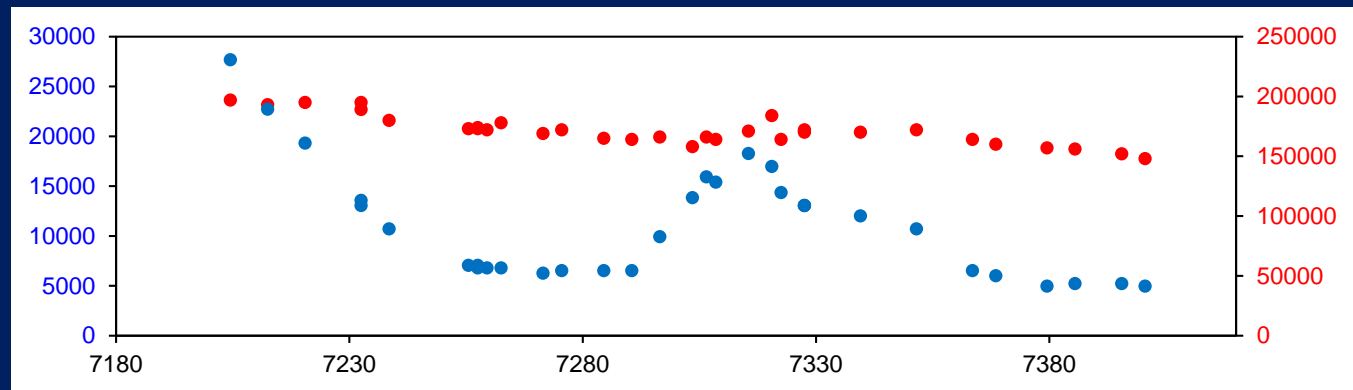
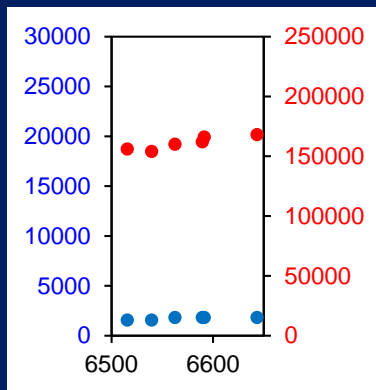
F. Teyssier
J. Guarro
O. Garde
K. Graham
T. Lester
V. Bouttard
T. Lemoult
U. Sollecchia
J. Montier
D. Boyd

Outbursts symbiotiques AG Peg 2015



Luminosité [L_{\odot}]

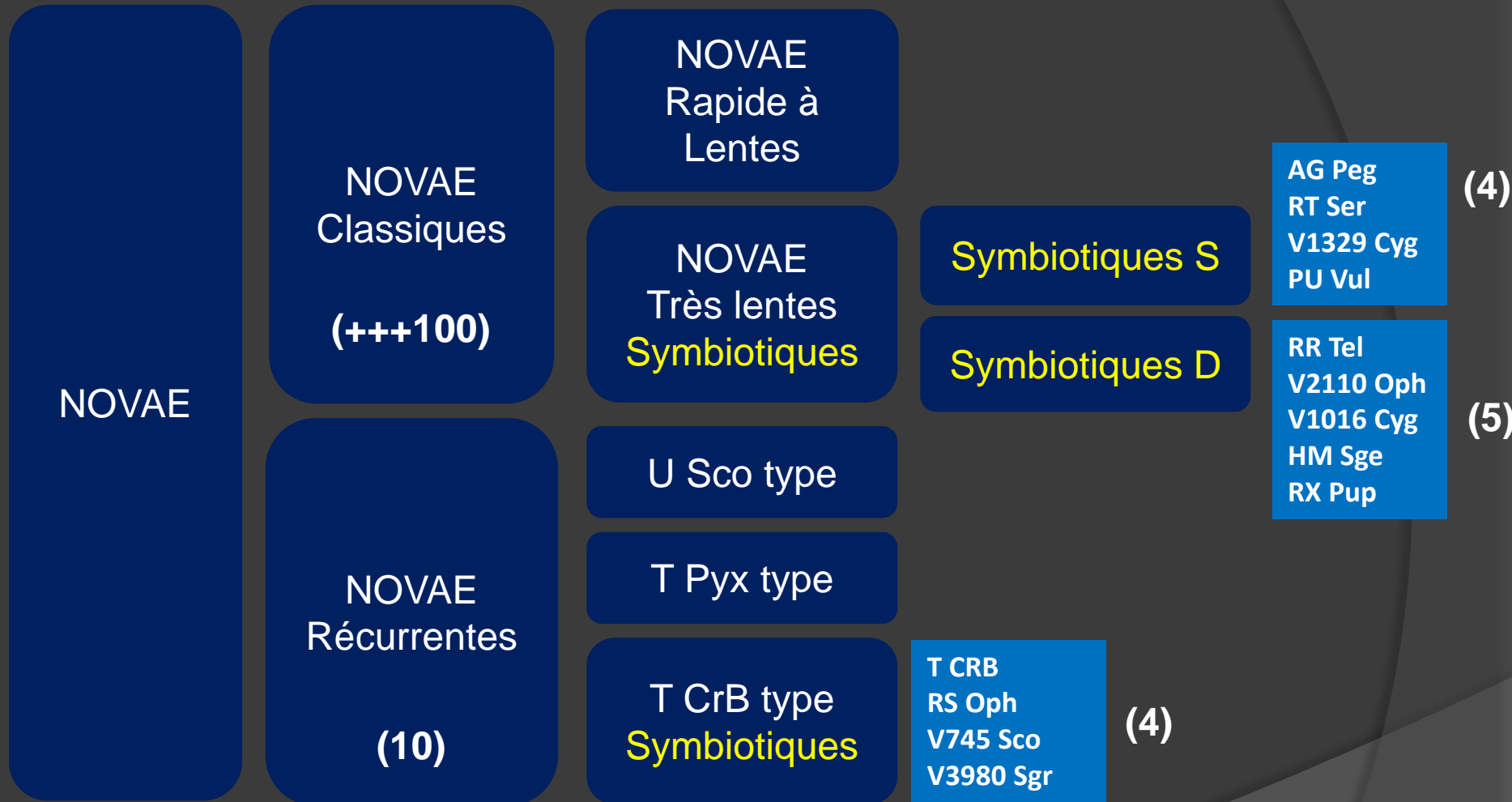
Température [K]



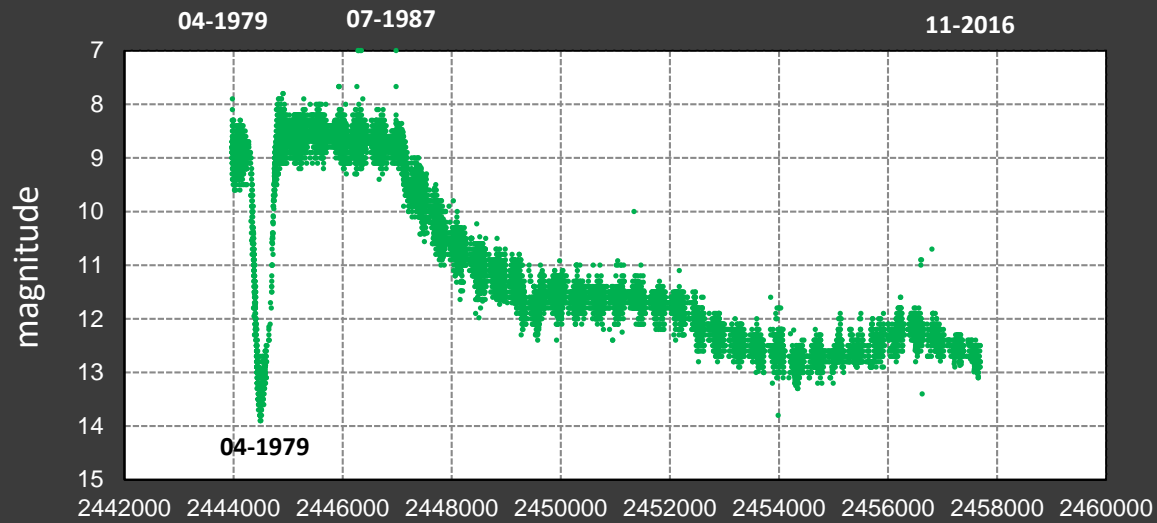
En cours de publication (Astronomy and Astrophysics)

New outburst of the symbiotic nova AG Peg after 165 years

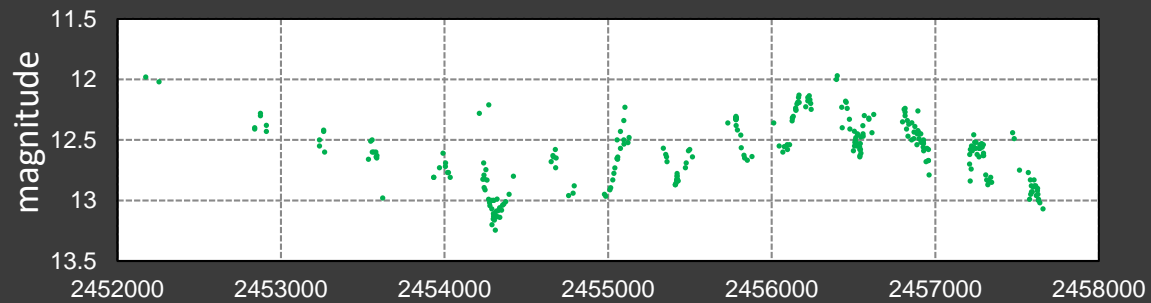
A. Skopal¹, S. Yu. Shugarov^{1,2}, M. Sekeráš¹, M. Wolf³, T. N. Tarasova⁴, F. Teyssier⁵, M. Fujii⁶, J. Guarro⁷, O. Garde⁸,
K. Graham⁹, T. Lester¹⁰, V. Bouillard¹¹, T. Lemoult¹², U. Solliecchia¹³, J. Montier¹⁴, and D. Boyd¹⁵



Novae Symbiotiques PU Vul



AAVSO
V + Vis.
LightCurve

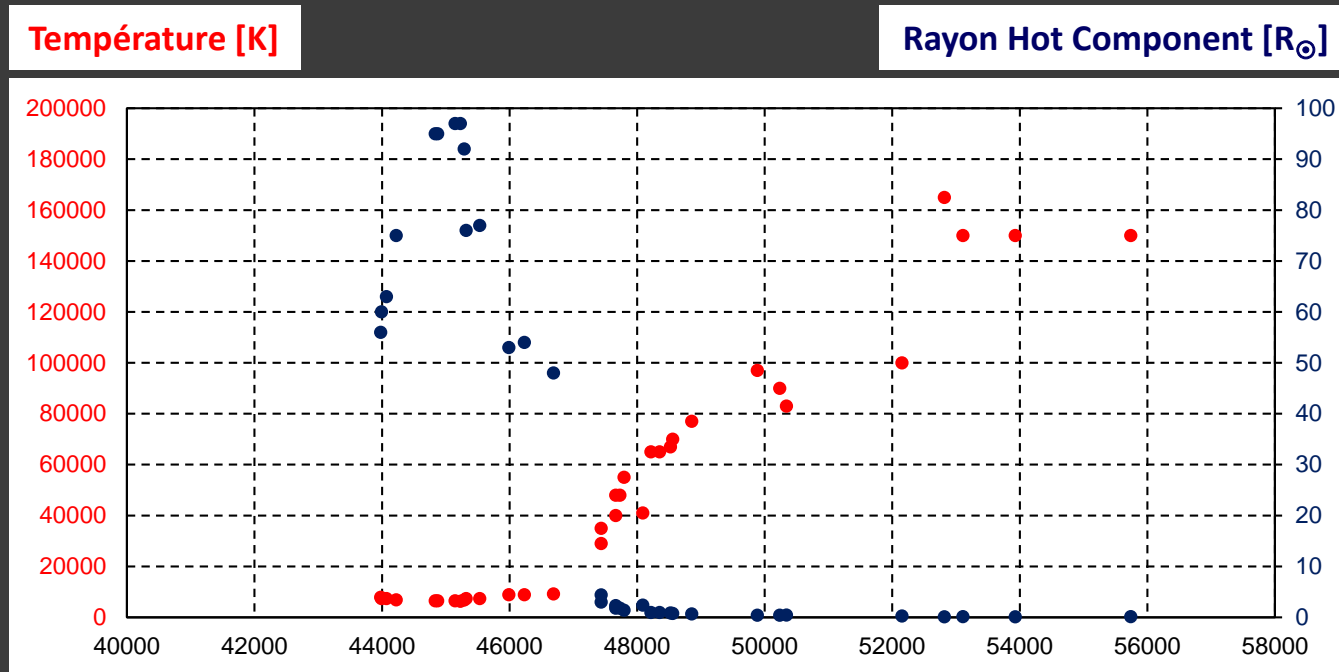


Variations orbitales AAVSO V

Novae Symbiotiques PU Vul

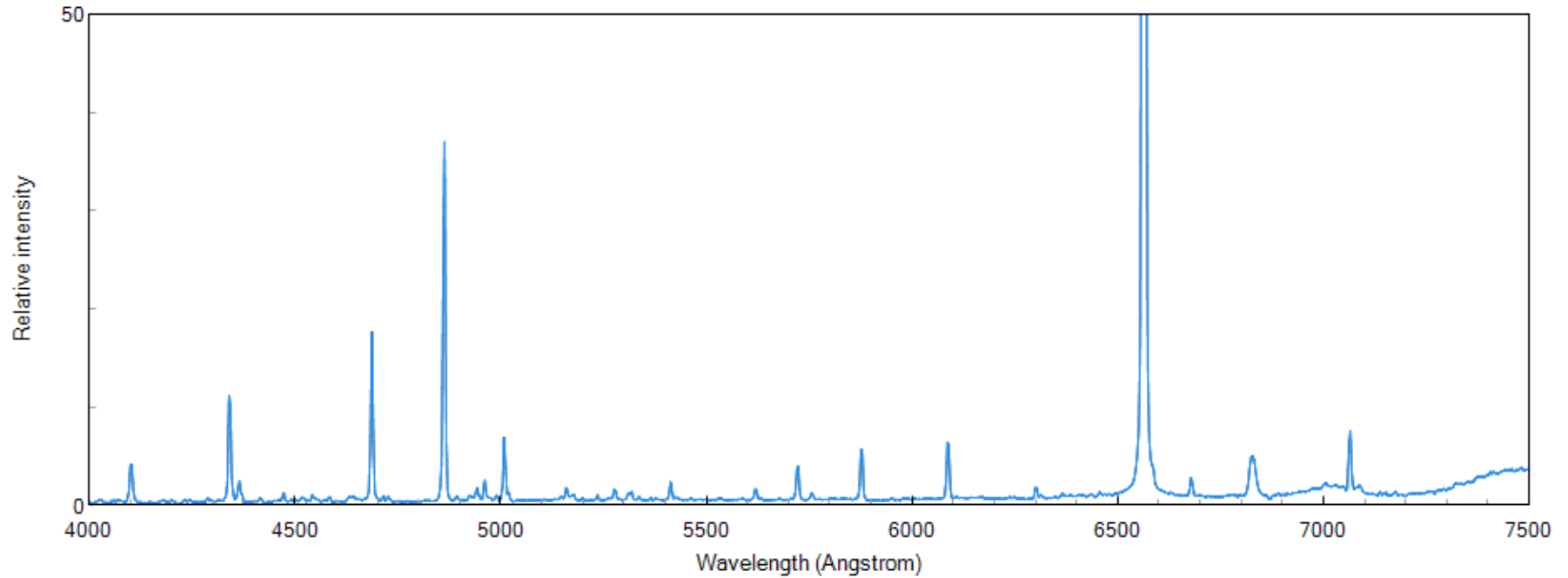
Evolution of the Symbiotic Nova PU Vul

Kato & al., 2012

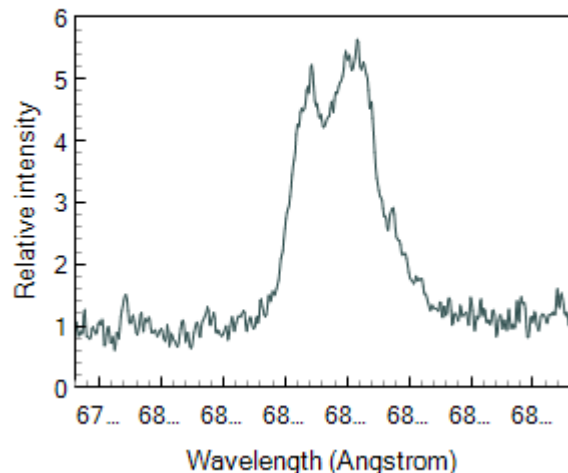


Novae Symbiotiques PU Vul

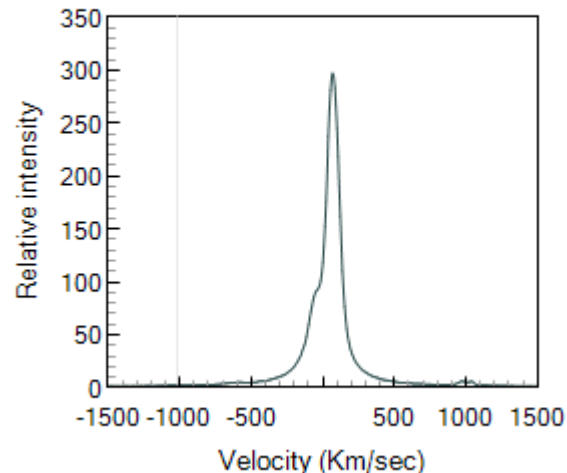
PUVul 2014-11-05.877 R = 1000 D.Boyd



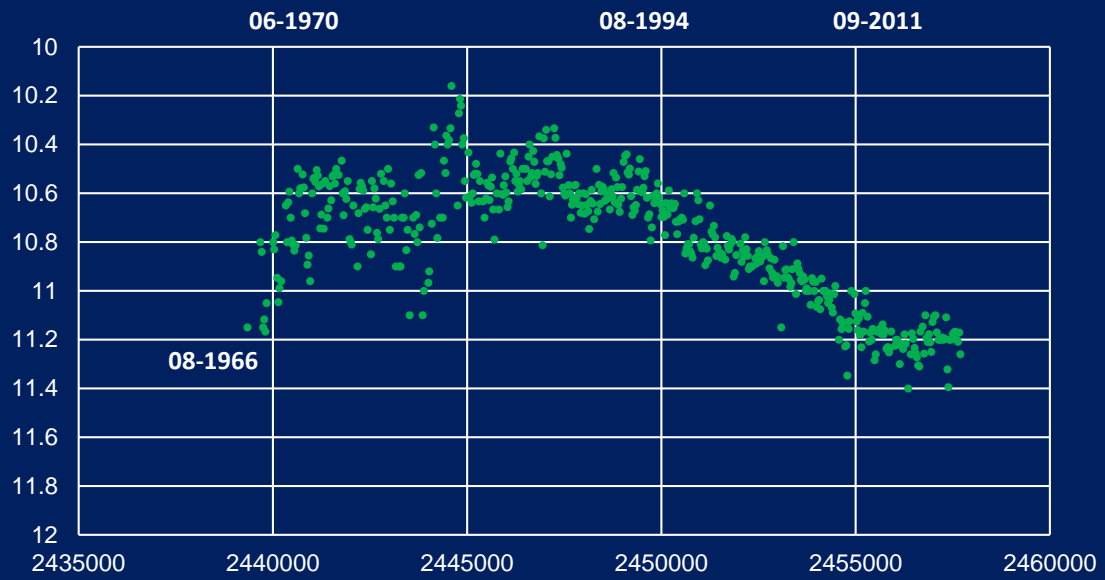
Raman OIV - PUVul 2016-09-03.041 T Lester



Halpha - PUVul 2016-09-03.041 T Lester

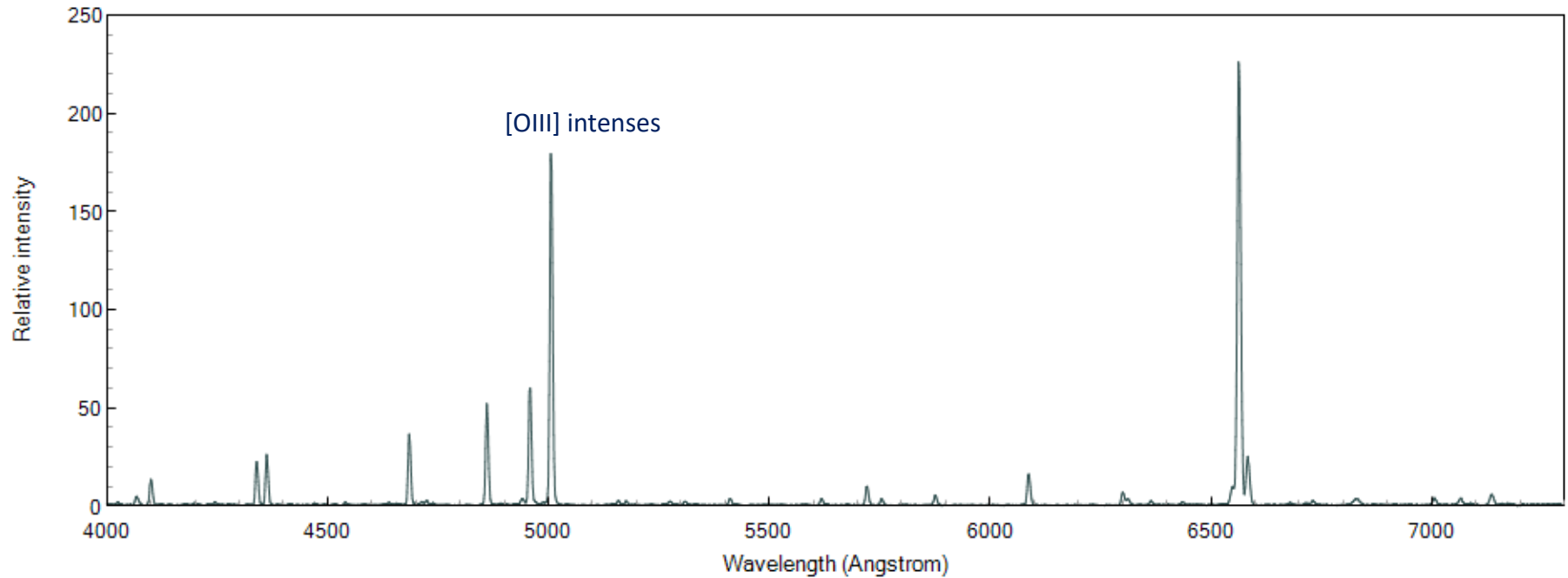


Novae Symbiotiques V1016 Cyg

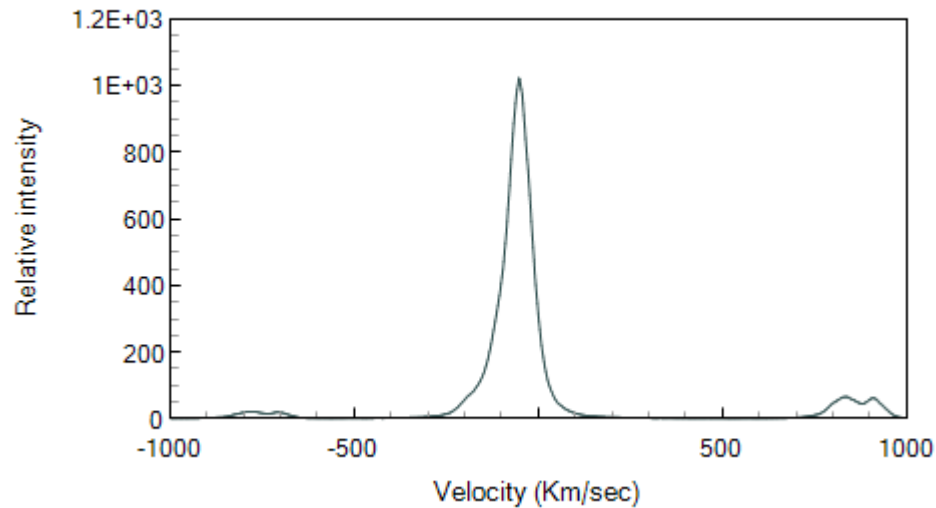


Novae Symbiotiques V1016 Cyg

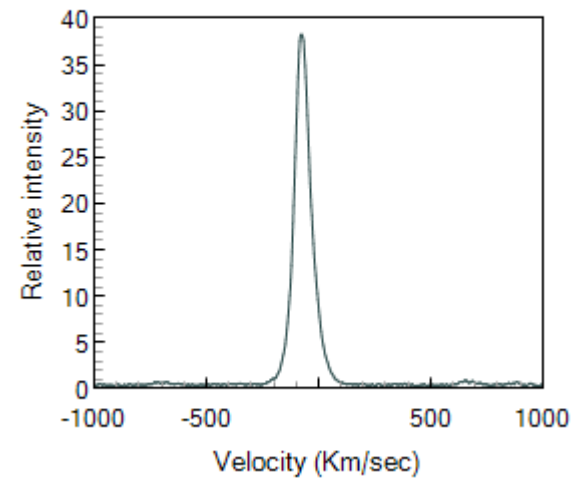
V1016 Cyg 2016-06-18.976 Francisco Campos



Halpna - V1016 Cyg 2016-10-04.773 F Teyssier



[FeVII] - V1016 Cyg 2016-10-04.773 F Teyssier

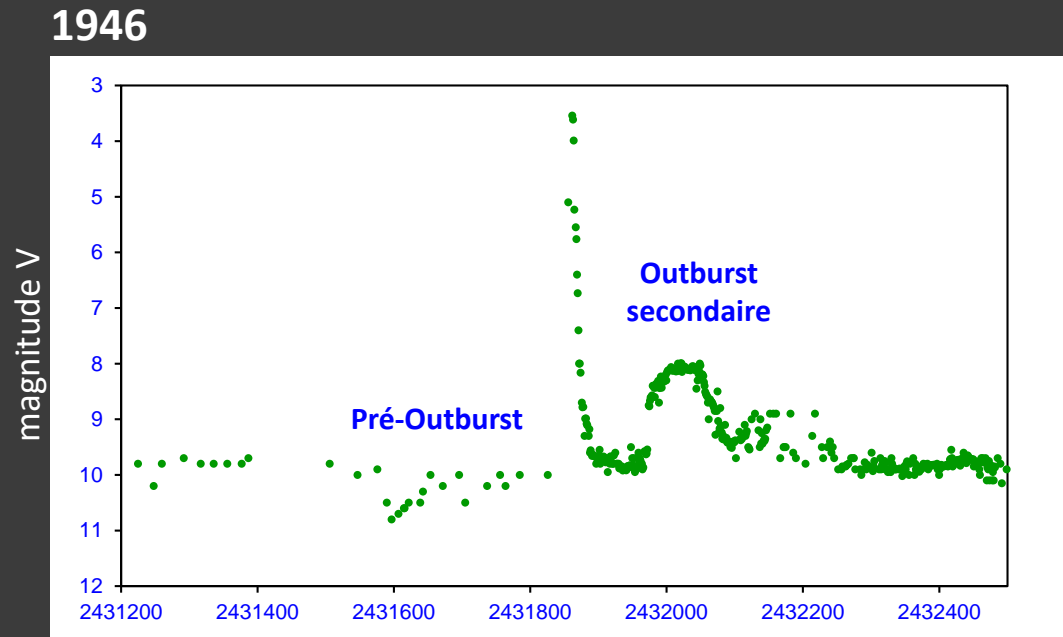


T CrB Eruptions

1866

1946

2026 ?



Active phases and flickering of a symbiotic recurrent nova T CrB

Krystian Bkiewicz,^{1*} Joanna Mikolajewska,¹ Kiril Stoyanov,²
Antonios Manousakis¹ and Brent Miszalski^{3,4}

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⁴Southern African Large Telescope Foundation, PO Box 9, Observatory, 7935, South Africa

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S. Charbonnel
F. Teyssier
C. Buil
T. Lester
C. Revol
JP Masviel
J. Montier
D. Boyd
J. Guarro
K. Graham
M. Rodriguez
P. Somogyi
O. Garde
P. Berardi
D. Li
V. Bouttard

Spectroscopic observations were obtained from the Astronomical Ring for Access to Spectroscopy database (ARAS). A log of observations is presented in Table A1. The data include mainly low resolution spectra covering a wide spectral range.

Voir aussi :

The 2015 super-active state
of recurrent nova T CrB
and the long term evolution after the 1946 outburst
Munari & al., 2016

Active phases and flickering of a symbiotic recurrent nova T CrB

Krystian Bkiewicz,^{1*} Joanna Mikolajewska,¹ Kiril Stoyanov,² Antonios Manousakis³ and Brent Miszalski^{3,4}

¹Nicolaus Copernicus Astronomical Centre, Bartyla 18, 80716 Warsaw, Poland

²Institute of Astronomy and National Astronomical Observatory, Bulgarian Academy of Sciences, Tsarigradsko Shosse, Sofia, Bulgaria

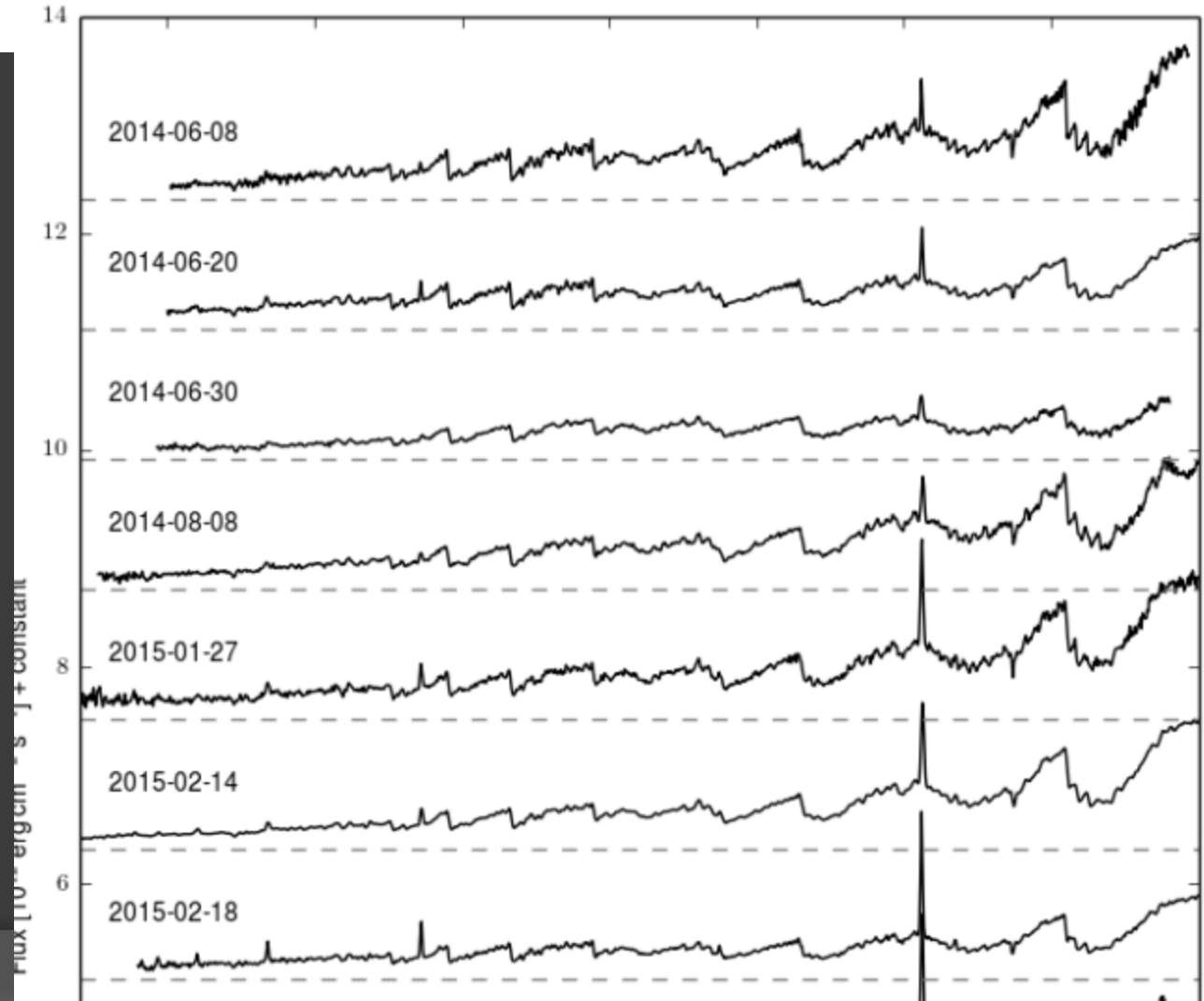
³South African Astronomical Observatory, PO Box 9, Observatory, 7935, South Africa

⁴Southern African Large Telescope Foundation, PO Box 8, Observatory, 7935, South Africa

Monthly Notices of the Royal Astronomical Society, Volume 462, Issue 3, p.2695-2705

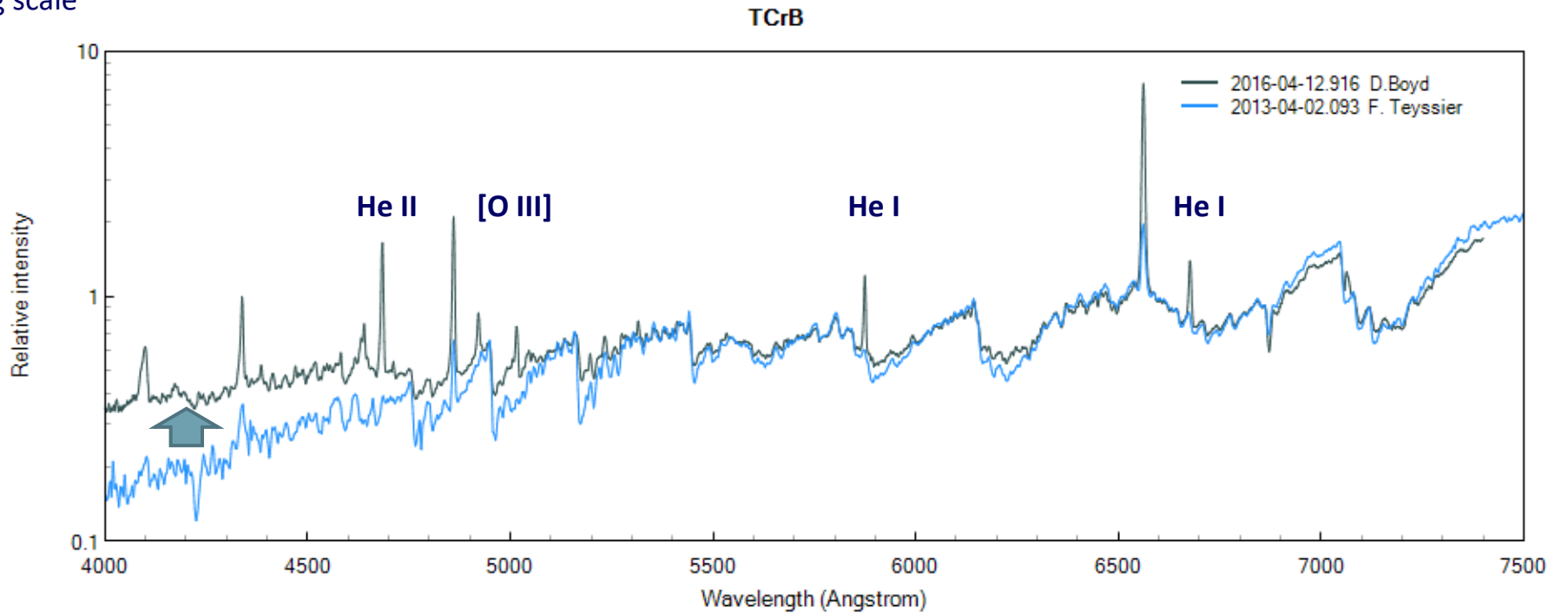
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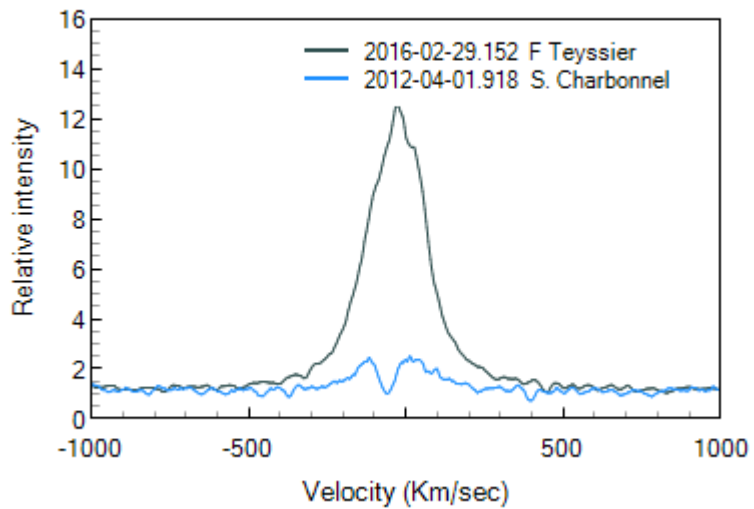
Novae Récurrentes Symbiotiques T CrB

Log scale

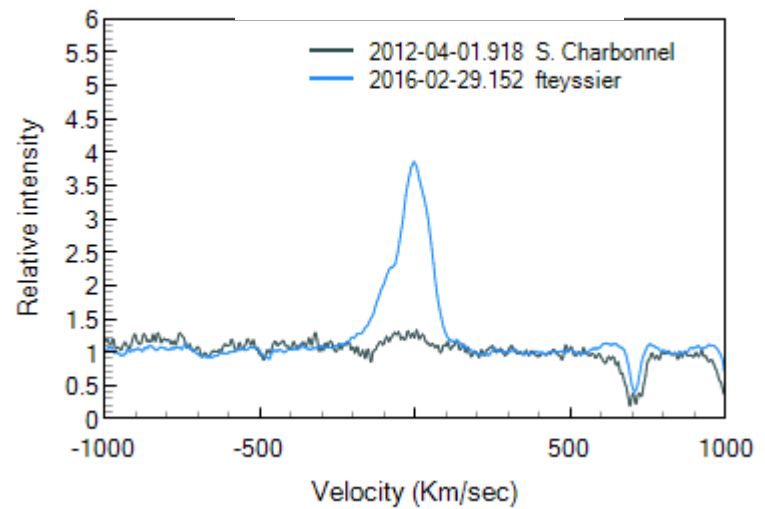


Novae Récurrentes Symbiotiques T CrB

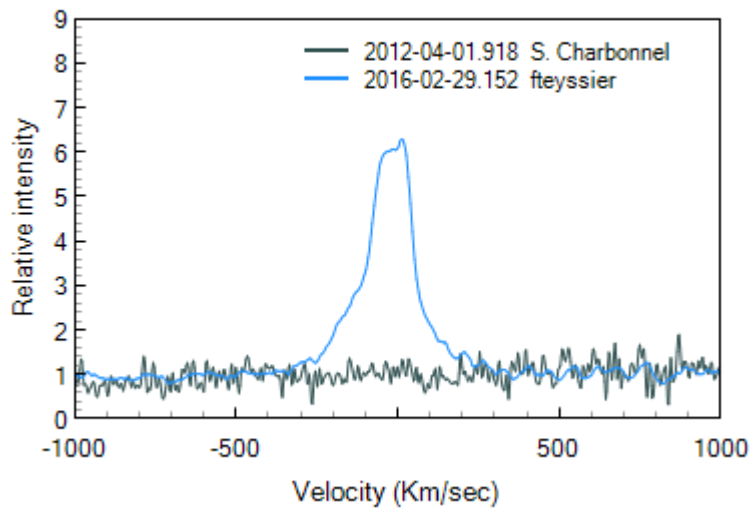
TCrB H alpha



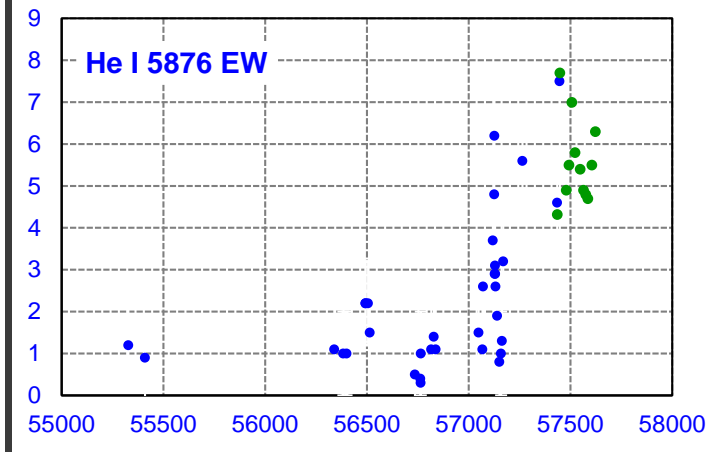
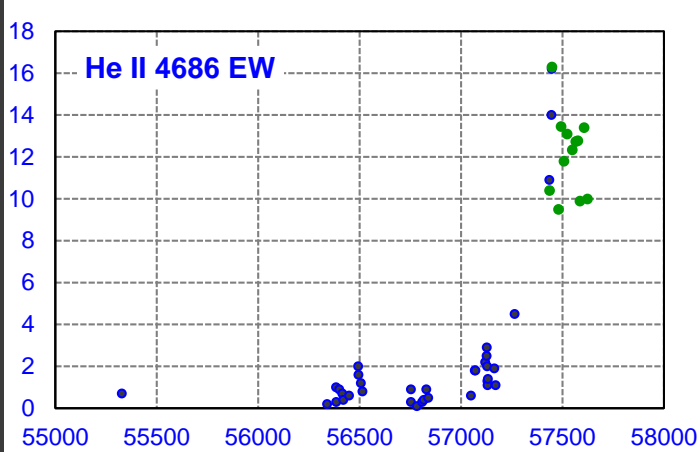
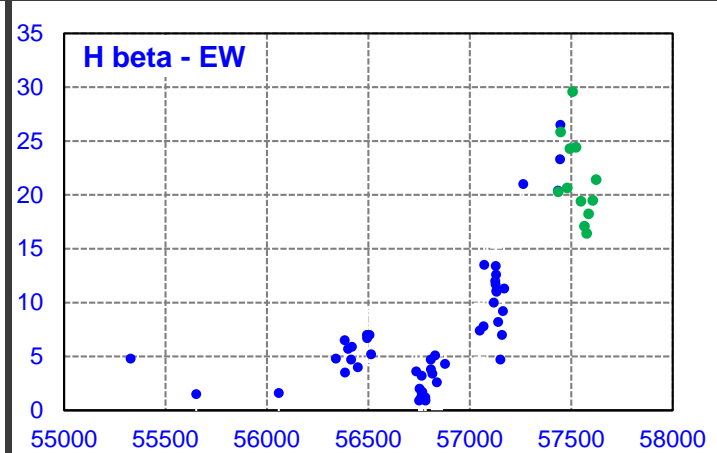
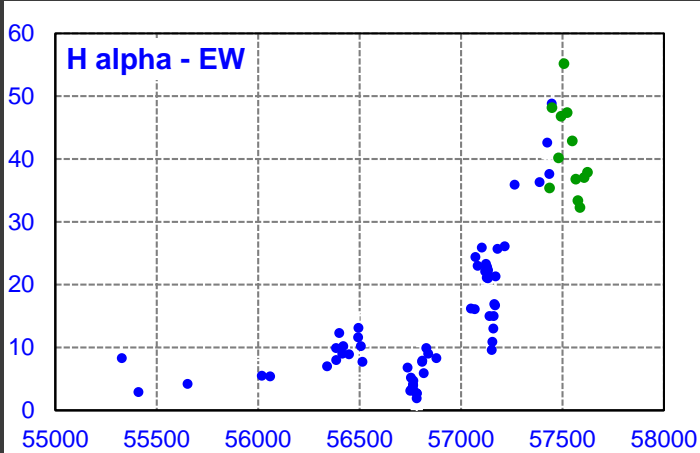
TCrB HeI 5876



TCrB HeII 4686



Novae Récurrentes Symbiotiques T CrB



Blue : mesures publiées (Liliczki & al., 2016)

Vert : mesures ARAS 2016

1 Spectroscopie et Classification spectrale

2 La découverte des Etoiles Symbiotiques

3 Modèle d'une Etoile Symbiotique

4 Formation du spectre

5 Les Symbiotiques à l'état calme

6 Le Zoo des Symbiotiques

7 Les Symbiotiques en Outburst

8 Contribution des amateurs

Merrill, 1958

L. H. Aller has made a suggestion which I heartily endorse, namely, that important information could be obtained from systematic series of measurements of *absolute* intensities of certain spectral features. This is not easy in observations through a slit, but with normal photometric precautions useful accuracy could doubtless be achieved on slitless spectrograms. Accurate photometric measures of integrated brightness and color also would be highly useful and could easily be made with small telescopes.

Persistent observations, both spectroscopic and photometric, for 5 or 10 years of the brighter symbiotic stars would surely help us understand their mysterious behaviour and might develop ideas of considerable general interest.

Réactivité

Suivis réguliers à haute cadence sur le long terme

[www.astronomie-amateur.fr/Projets Spectro1 SySt.html](http://www.astronomie-amateur.fr/Projets_Spectro1_SySt.html)

Lettre information

Eruptive stars information letter

<http://www.astrosurf.com/aras/novae/InformationLetter/InformationLetter.html>

Forum ARAS

<http://www.spectro-aras.com/forum/>

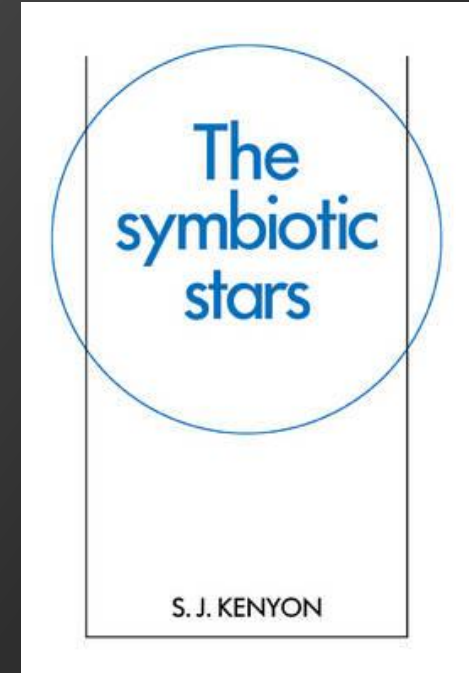


Base spectrale

http://www.astrosurf.com/aras/Aras_DataBase/Symbiotics.htm

A.R.A.S Spectral Data Base - Eruptive stars section

Symbiotic stars



Seul livre existant
Réédition en 2008 de l'édition 1986,
sans mise à jour



HARDY

Merci pour votre attention